Advancing Skill Learning in Neurorehabilitation through

Dance and Biomechanics.

by

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Thesis

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SUBMISSION DECLARATION

I declare that the submitted material is not substantially the same as published or unpublished material that I have previously submitted, or am currently submitting, for a degree, diploma, or similar qualification at any university or similar institution. No parts of the works presented in this thesis have been submitted previously for any aforementioned qualification.

WORD COUNT 16992

LIST OF PUBLICATIONS INCLUDED IN THE THESIS

List of publications submitted for consideration for the degree of Doctor of Philosophy by Published Work with statements of the candidate's contribution to the published work

These papers can be found in Appendix A

Papers with Statement of Contribution	**Authorship**
Paper 1 **New Partnerships Between Dance and Neuroscience: Embedding the Arts for Neurorecovery** **Dance Research Journal 2011 29.2, 469-496.** L Worthen-Chaudhari conceived of and executed this research in its entirety.	**Worthen-Chaudhari, L**
Paper 2 **A feasibility study using interactive graphic art feedback to augment acute Neurorehabilitation therapy** **NeuroRehabilitation 2013 33(3), 481-490.** L Worthen-Chaudhari conceived the idea of this research, designed the study and data collection, performed all data analysis, and led manuscript preparation. W. Mysiw oversaw clinical aspects of implementation in the acute rehabilitation hospital in which the research was performed, where he serves as Academic Chair and Medical Director. MA Bockbrader contributed to study and statistical analysis design. The following authors represent	**Worthen-Chaudhari, L*** Whalen, CN Swendal, C Bockbrader, MA Haserodt, S Smith R Kelly Bruce, M Mysiw, W

practicing clinicians who recruited clinician participants and contributed to interpretation of results: CN Whalen (for physical therapy), C Swendal (for occupational and recreational therapy), and W Mysiw (for physiatry). Dance faculty author M Kelly Bruce acted to confirm that the augmentative arts feedback was designed in keeping with relevant art theory related to Abstract Expressionism, Dance Technology, interactive art, and creative movement generation. Data collection was performed by L Worthen-Chaudhari, S Haserodt, R Smith. All authors contributed to and approved the final manuscript.	
Paper 3 **A new look at an old problem: Defining weight acceptance in human walking** **Gait & Posture 2014 39(1), 588-592.** L Worthen-Chaudhari, DM Basso, and JP Schmiedeler conceived the idea of this research. Worthen-Chaudhari managed all data collection and analysis as well as led manuscript writing including figure generation. Bing worked as a research assistant performing data analysis as supervised by Worthen-Chaudhari. Basso supervised design of the work such that it would fundamentally aid translational work from animal to human models, as well as data interpretation and manuscript preparation.	**Worthen-Chaudhari, L*** Bing, J Schmiedeler, JP Basso, DM

Schmiedeler supervised biomechanical data analysis, as well as data interpretation and manuscript preparation.	
Paper 4 **Training conditions that best reproduce the joint powers of unsupported walking** **Gait & Posture 2015 41(2), 597-602.** L Worthen-Chaudhari, DM Basso, and JP Schmiedeler conceived the idea of this research. Worthen-Chaudhari conceived this investigation and designed data analysis, managed all data collection and analysis, and led manuscript writing, including figure generation. Basso supervised design of the work such that it would fundamentally aid translational work from animal to human models, as well as supervising data interpretation and manuscript preparation. Schmiedeler supervised biomechanical data analysis, as well as data interpretation and manuscript preparation.	**Worthen-Chaudhari, L*** Schmiedeler, JP Basso, DM
Paper 5 **Characterizing within-subject variability in quantified measures of balance control: a cohort study** **Gait & Posture 2018** L Worthen-Chaudhari conceived the idea of this research and supervised every aspect of the research. C Bland conducted data acquisition. SM Monfort contributed to study design as well as biomechanical and statistical data	**Worthen-Chaudhari, L*** Monfort, SM Bland, C Pan, X Chaudhari, AMW

analysis and interpretation. X Pan designed statistical analysis. AMW Chaudhari contributed to study design and data interpretation. All authors contributed to and approved the final manuscript.	

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LIST OF ABBREVIATIONS

(alphabetical order)

BWS = Body Weight Support

CIMT = Constraint-Induced Movement Therapy

COP = Center of Pressure

GRASP = Graded Repetitive Arm Supplementary Program

iSCI = Incomplete Spinal Cord Injury

KP = Knowledge of Performance

KR = Knowledge of Results

LE = Lower Extremity

MRC = Medical Research Council, UK

NIH = National Institutes of Health, US

OT = Occupational Therapy

PCO= Patient-Centered Outcomes

PCORI = Patient-Centered Outcomes Research Institute, US

PT = Physical Therapy or Physiotherapy

STEAM = Science, Technology, Engineering, Art, and Math

STEM = Science, Technology, Engineering, and Math

TBI = Traumatic Brain Injury

TR = Recreation Therapy

Tx = Treatment

UK = United Kingdom

US = United States

WSV = Within-Subject Variability

1 SUMMARY OF THESIS

This thesis presents published work advancing Neurorehabilitation science. At the outset of the work (2010), gaps in knowledge impeded the investigation of neurosensorimotor recovery from neurotrauma. To begin to fill these gaps, I investigated engagement of the human system on two fronts: dance (Papers 1,2) and biomechanics (Papers 3-5). In Aim 1 of this thesis, I investigate application of arts-based concepts to performance of activity-based training, presenting 2 papers that established dance technology as augmentative for hospital-based Neurorehabilitation treatment. In Aim 2, I investigate biomechanics within the context of activity-based training, presenting 3 papers that characterize the dynamic solution space – or manifold – of healthy gait and posture to establish quantitative, physics-based parameters of clinical practices relevant to locomotor and balance Neurorehabilitation.

Aim 1

Paper 1 presents a state-of-the-art review of implicit learning theory and reports the first ever design study of dance technology applied to Neurorehabilitation of physical skills among clients with neurotrauma.

Paper 2 reports, for the first time in a medical journal, feasibility of implementing dance technology to augment acute, hospital-based Neurorehabilitation care.

Aim 2

Paper 3 redefines the weight acceptance phase of unimpaired human locomotor skill in a manner that translates between quadrupedal and bipedal walking across a clinically relevant range of speeds.

Paper 4 characterizes the solution space of unimpaired walking dynamics in a manner that informs clinical training to rehabilitate walking skill among individuals with paralysis.

Paper 5 characterizes the dynamical solution space of unimpaired postural control in a manner that advances longitudinal, biomechanical assessment of balance skill deficits within clinical practice.

These five papers represent pioneering work in Neurorehabilitation, establishing a foundation from which to advance human recovery from neurotrauma by applying dance and biomechanics to advance skill learning in Neurorehabilitation.

2 BACKGROUND

2.1 STATEMENT OF APPROACH

I came into this work as a dance artist and a research biomechanist: two professional practices involving close study of movement. In the two decades preceding the studies presented in this thesis, I accumulated professional and academic experience in the art and the science of movement as separate disciplines, studied in parallel. In dance, I earned scholarly degrees in Fine Arts (BFA 1994, MFA 2011) and worked professionally with Company Chaddick, a contemporary dance company located in San Francisco, CA (2003-2006). In biomechanics, I completed a post-graduate degree with Dr. Joseph Hamill (MS 1999), then worked as a research biomechanist for Drs. Steven Kautz (2000-2005), Gary Beaupre (2003-2005), and Thomas Andriacchi (2005-2006). In 2010, I was supported by Professor Jerry W. Mysiw, Chair of the Department of Physical Medicine and Rehabilitation at The Ohio State University, to pursue independent research in Neurorehabilitation science.

I approached this independent work through the lenses of dance and biomechanics. Applying relevant research approaches, I published five papers, presented for consideration in this thesis, that were motivated by the same question: **could activity-based training be optimized to further advance functional recovery after neurotrauma**? All 5 papers are influenced by Dynamic Systems Theory (DST), which avers that living systems self-organize, implicitly, in response to physical stimuli (e.g., gravity, inertia, movement).

From the central question I saw potential for advancing skill learning in Neurorehabilitation through both dance and biomechanics. Dance-based paradigms might help to motivate performance of therapeutic movement among individuals with combinatorial cognitive and motor deficits. Biomechanical measurement of movement dynamics might help to improve clinical treatment and assessment. I approached the central question of the thesis from these two fronts: dance (Aim 1; papers 1,2) and biomechanics (Aim 2; papers 3-5). Papers 1 and 2 establish that dance theories and processes are feasible to apply within hospital-based Neurorehabilitation, as an avenue to engage clients with a range of cognitive and motor deficits. Papers 3-5 begin to characterize the dynamic manifold relevant to locomotor (Papers 3-4) and balance (Paper 5) recovery. Methodologies used per paper differ from ecological momentary assessment in papers 1 and 2 to biomechanical quantification in papers 3-5. Also, modes of communication differ per paper, from humanities-focused discursive style in paper 1 to hypothesis-driven scientific articulation in papers 2-5. All papers, however, advance the science of health recovery following neurotrauma, applying an empirical research approach to study Neurorehabilitation (papers 1-5).

2.2 CONCEPTS RELEVANT TO THE THESIS

2.2.1 Neurorehabilitation Medicine-Related Concepts

2.2.1.1 Neurotrauma

Neurotrauma occurs when the nervous system is damaged as in the case of traumatic brain injury (TBI), spinal cord injury (SCI), chemotherapy-induced neuropathy (CIN), or a host of other neural insults that can result in persistent deficits that impair performance of functional skills. Prevalence and consequences of neurotrauma are dramatic. For instance, the Lancet Neurology Commission reports that about half the world's population will sustain at least one TBI over their lifetime with potential consequences including loss of basic human functions such as movement, concentration, and emotional regulation acutely or chronically[1]. Furthermore, the impact of neurotrauma extends to the social network of caregivers for individuals with neurotrauma (e.g., spouse, partner, family member), indicating an impact to society beyond loss of independence for the individual who is injured[1].

2.2.1.2 Neurorehabilitation

Functional skills such as walking and attention that are automatic for persons without neural deficit can become challenging or impossible to perform when automaticity is lost due to neurotrauma. Neurorehabilitation seeks to restore healthy function through stimulating neurorecovery of the person's physical system. If attempts to stimulate neurorecovery fall short of full restoration, Neurorehabilitation guides persons with neurotrauma to implement compensatory strategies and technologies [2,3]. The work presented in this thesis is concerned with stimulating restoration of automaticity in functional force production. To achieve this end, the work focuses on addressing the design of interventions for physical skill acquisition after neurotrauma.

2.2.1.3 Anatomy and Physiology

2.2.1.3.1 Muscles

Muscle fibers represent the motor of the human neurosensorimotor system. Proteins within these fibers interact to contract the muscle, thus creating force and skeletal movement. Importantly, while these proteins are in a state of contraction, the muscle fiber can shorten or lengthen to accelerate or decelerate skeletal motion, respectively. Shortening contractions are termed “concentric” while lengthening contractions are termed “eccentric”. Concentric and eccentric contractions behave differently in terms of mechanics. Eccentric muscle fiber contractions generate more force per unit of fiber movement than concentric muscle fiber contractions[4]. The exact mechanism of this force differential remains to be identified and is the subject of much study.

Concentric and eccentric contractions also behave differently in terms of motor control – an area of inquiry that represents my main interest in the neurophenomenon. Voluntary concentric activity can be produced relatively simply, by brain activation of efferent activity (e.g., push a door, kick a ball). Eccentric activity, on the other hand, requires complex subcortical signaling between afferent and efferent neurons through interneurons within the spinal cord[4]. Eccentric activity is considered a hallmark of mastery within skill performance[4]. It is a goal of Neurorehabilitation to restore both concentric and eccentric force production capacity.

2.2.1.3.2 Neurons

Information travels in the body along axonal projections that are categorized as efferent neurons, afferent neurons, or interneurons. Information traveling away from the central nervous system (CNS) (i.e. muscle excitation signaling) is categorized as efferent. Information traveling toward the CNS (i.e. sensory signaling) is characterized as afferent. Interneurons, found exclusively in the CNS, create a bridge between efferent and afferent neuronal projections. This terminology is relevant to the current thesis because activity-based training seeks to optimize afferent stimulation and efferent output.

2.2.1.4 Motor Control and Learning

The study of coordination and regulation of movement[5] is addressed within the fields of motor control and motor learning. By most accounts, these fields first became formalized as areas of scientific study when Bernstein (1967) used an experimental approach to investigate multi-joint control of the degrees of freedom involved in coordinated, functional movement. In the landmark book chapter, “The Co-ordination and Regulation of Movement”, Bernstein concluded that movement must be self-organizing and represented within the CNS [5]. Thereafter, motor control and motor learning emerged as related fields addressing CNS-based control of movement performance and acquisition, respectively. Within this thesis, sometimes literature from motor learning is grouped under the heading of motor control.

2.2.1.4.1 Implicit Control of Movement Dynamics

Control of movement dynamics involves a type of CNS guidance, described as implicit[6], in which physical skill performance is accomplished without conscious awareness or ability to verbally articulate the rules underlying performance of the skill[6,7]. One classic example of implicit control involves riding a bike. This skill cannot be mastered through linguistic instruction, whether written or verbal. To learn to ride a bike requires the learner to engage in the action of riding a bike. The successful learner will attempt to ride the bike, allowing their system to construct tacit knowledge through physical, non-verbal experience. Through repeated, ecologically valid, neurosensorimotor exposure (i.e., “trial-and-error”) the living system autonomously and implicitly maps solution space, building knowledge regarding the rules of successful skill performance.

2.2.1.4.2 Implicit Skill Learning After Neurotrauma

For skill learning after neurotrauma to succeed, implicit control must be available and leveraged. Research confirms that implicit control and learning processes may remain available to individuals who have had severe TBI[8], iSCI[9], and mild and moderate stroke[10], although speed and variability in motor performance and learning are influenced by loci and severity of the injury[11]. Of the implicit skill learning paradigms tested among persons with neurotrauma, multiple protocols have reported the promise of one strategy: activating the nervous system below the level of the injury in activity-based training scenarios. The following standardized, activity-based training protocols have evidenced partial restoration of hand, arm, balance, and/or locomotor function in a variety of neuropathologies: patient-administered graded repetitive arm supplementary program (GRASP)[12], therapist-administered constraint-induced movement therapy (CIMT) [13], and trainer-administered locomotor training[14–16]. However, recovery using existing training programs is far from universal, and innovation in the field is needed to drive more recovery for more people. My work seeks to improve on evidence-based movement therapy to maximize implicit learning of physical skills after neurotrauma[9,17–25].

2.2.1.4.3 Experience-Dependent Plasticity After Neurotrauma

It is critical for clients to retain skill learning beyond the end of a single Neurorehabilitation session. Retention does not always follow learning, especially when cognitive deficits complicate the client's skill recovery journey. The proposed mechanism underlying retention of motor learning after neurotrauma involves "neuroplasticity", a process involving CNS remodeling that is sometimes referred to as "experience-dependent plasticity"[26,27] or simply "plasticity". In this neurophenomenon, skill recovery after neurotrauma is attributable to remodeling of central nervous system tissues. We are just beginning to uncover best practices for inducing experience-dependent plasticity of the human system, however, and study of this neurophenomenon within adult rehabilitation from neurotrauma is relatively new.

On a practical level, the experience-dependent nature of plasticity means that Neurorehabilitation must deliver activity-based training. Delivering activity as a form of physical medicine for individuals with neurotrauma presents at least two dilemmas: 1) the client must intrinsically attend to the training activity and 2) the clinician must deliver optimal external stimuli during the training activity. The work presented in this thesis begins to address these two dilemmas. Client attention to therapeutic motion performance is advanced through arts-based methods of movement performance. External stimuli associated with activities performed are characterized using biomechanical methods for quantifying movement dynamics.

2.2.2 Biomechanics-Related Concepts

2.2.2.1 Movement Dynamics

The term "dynamics" has been used in subtly different ways by different disciplines (e.g., dance, physics). Within this thesis, I use the classical mechanics definition of dynamics, in keeping with definition of the term in biomechanics. Dynamics refers to the forces, or kinetics, underlying the motion of objects with mass[28]. Classical mechanics and the field of biomechanics apply Newton's laws of motion[29] to define and study dynamics.

2.2.2.2 Dynamical Systems Theory

Dynamic or Dynamical Systems Theory (DST) arose as a leading approach to conceptualize the biophysical signals underlying action and cognition as temporal, changing, and interrelated[30,31]. Because DST represents a classical mechanics-based approach to motor control and learning, for the purpose of this thesis I place DST within Biomechanics-Related Concepts. Nonetheless, many authors in the DST tradition are known as pioneers of motor control/learning research (e.g., Ann M. Gentile (1936-2016), Esther S. Thelen (1941-2004)). Because DST predicts system remodeling in response to physical stimuli, the approach represents a potentially critical link between the fields of biomechanics and motor control.

Gentile, an early pioneer of motor learning with publications extending back to the 1970s, articulated the DST approach as viewing motor control to be a "problem of organized complexity"[7] wherein self-organization of the organism occurs as a consequence of interactive transfers of energy[7] with the world around it. While nebulous, her definition is fundamentally important for the way that she grounds motor control theory in physical laws of nature. The human organism represents a dynamic system[30] that is negentropic (i.e., resists entropy or disorder), temporally-structured (i.e., unfolds in time), and interactive with its environment[7]. Thus the stochastic, chaotic, and/or redundant neural components of the human system[32] can be expected to self-organize to prevent disorder in our interactions with the world. In short, physical skill behavior is predicted to organize systematically in response to physical phenomena (e.g., gravity, inertia, pressure).

2.2.2.2.1 Manifold

In addition to grounding motor control in physical laws of nature, DST provides analytic constructs with which to model and conceptualize relevant neurophenomena. One such construct involves the mathematical concept of a manifold which defines a set of solutions, or a *solution space*[33,34]. When applied to movement, the manifold concept can be used to define the solution space within which motion is implicitly controlled. The concept of the manifold is relevant for this thesis in that all 5 papers seek to advance access of persons with neurotrauma to the solution space of stable motion behavior, with the assumption that practicing within this manifold will stimulate recovery of implicit control. Operationally, the manifold within which clients are guided to practice is at the intersection of the client's existing and desired function.

Within this thesis I refer to the solution space of stable, functional movement behavior as the "*dynamic manifold*". As an example of a dynamic manifold, consider locomotor function wherein there exists an envelope of possible solutions (i.e., manifold) within which the lower extremity (LE) joints operate to produce coordinated walking. Within this manifold, some variability is tolerated in movement within and between joint actions. However, if the LE joints operate outside of this manifold, locomotor function fails because the system fails to locomote through rigidity or collapse. This conceptualization differs from the Uncontrolled Manifold Hypothesis[33], in that no presumptions are made about the source of dynamic control.

2.2.2.2.2 Optimal Movement Variability

The dynamic systems perspective also provides insight into the neural phenomenon of movement variability, which has been called a hallmark property of biological systems[32,35–37]. Some manifold of movement variability is healthy, even essential for functional motor control[38,39]. Human movement science[35] and physical therapy[37] have been criticized for ignoring the essential role of variability in dynamic stability. Stergiou, Harbourne, and Cavanaugh (2006) proposed the theory of "Optimal Movement Variability" to articulate restoration of variability as an explicit goal of Neurorehabilitation[37]. This theory conceptualizes optimal movement variability as occurring within the manifold of stable, implicitly controlled movement behavior. Greater than optimal movement variability indicates noise and instability. Less than optimal movement variability indicates rigidity. Both greater than and less than optimal movement variability represents neuromotor impairment. Therefore, to achieve functional restoration, Neurorehabilitation training must seek to restore optimal movement variability[32,37] within the dynamic manifold.

2.2.2.2.3 Dynamic Walking Approach

The dynamic systems perspective also supports the dynamic walking approach[40–42] which reframes the gait cycle as a function of mechanical work. This approach avers that mechanical and metabolic work performed within the gait cycle can be explained by passive dynamics with one exception: the dynamic collision between the leading foot and the ground that marks the beginning of the weight acceptance phase. Represented experimentally as lower extremity power absorption, the negative work occurring at and just after foot contact represents one aspect of gait that cannot be modeled by a passive robot[43]. The dynamic walking approach predicts that metabolic work performed during walking can largely be attributed to joint power occurring during double support (i.e., weight acceptance and terminal stance), with important implications for Neurorehabilitation of locomotor function post neurotrauma[42].

2.2.2.3 Joint Power

The mathematical construct of joint power represents a biomechanical variable that allows translation between the dynamic walking approach (section 2.2.2.2.3), eccentric and concentric muscle contraction (section 2.2.1.3.1), and motor control investigations of implicit learning post neurotrauma (section 2.2.1.4.2). Net power for a joint (e.g. knee, hip, elbow) is calculated as the product of the moment and angular velocity of that joint. If the product is positive (i.e., both moment and velocity are positive or both are negative), this indicates that the joint is generating power. If the product is negative (i.e., the two quantities have opposing signs), this indicates that the joint is absorbing power. When a joint demonstrates net power generation or absorption, the agonist muscles about that joint must be acting concentrically (i.e., shortening while producing force) or eccentrically (i.e., lengthening while producing force), respectively. The neural signaling to, and force production capacity of, muscles change in characteristic ways within concentric vs. eccentric muscle fiber contractions[4]. Therefore joint power, as a measure, provides insight relevant for both biomechanical and motor control research paradigms[44,45] Because joint power generation/absorption maps intuitively to work performed, muscle action, and neural control by the client, I favor this reporting convention to bridge biomechanics to motor control research and facilitate interdisciplinary investigation of Neurorehabilitation treatments.

2.2.3 Arts-Related Concepts

2.2.3.1 Dance

Dance is the art of motion and is dedicated to exploration of movement as an abstract form[46]. Because dance forms explore movement, to practice dance is to explore the realm of dynamics, implicitly. Dance curriculum studies the dynamics of motion through arts-based methods rather than teaching the scientific formulations of motion. Nevertheless, dance pedagogical methods serve to build tacit knowledge about one's dynamic manifold and characteristic force dynamics (e.g., inertia of limbs; control of body acceleration/deceleration; interpretation of creative choice as movement coordination, etc.).

It is important to note that dance has been, and continues to be, mischaracterized as story-telling through expressive movement[46](p.48) or limited to movement performed to rhythmic music (movement-to-music)[47]. While some famous ballets do tell a story through emotive gestures, the art form of dance is not dependent on expressive movement. Similarly, while popular and social forms of dance are generally performed to rhythmic music, the art form of dance is not dependent on musical accompaniment. For examples of dance as a stand-alone art, dedicated to exploration of movement as an abstract construct vs derivative of pantomime or music, see the works of choreographers Merce Cunningham[48], Trisha Brown[49], and Elizabeth Streb[50] among many other notable pioneers of the art of dance.

2.2.3.2 Dance Technology or Interactive Art

Dance technology is a genre of interactive art that involves a responsive dialogue between the participant and the environment and is usually mediated through technology such as biophysical sensors. When crafted from the perspective of dance technology, interactive art applications encourage movement explorations. For instance, Rafael Lozano-Hemmer's Pulse Park (Lozano-Hemmer, 2008), an interactive art installation exhibited in 2008 (Madison Square Park, New York City, New York, US), detects the heart rate of individuals within the park and updates aspects of the environment, such as spotlight brightness, in response to the heart beats detected. In this installation, individuals can change the environment by exploring qualities of their personal activity performance (e.g., velocity of motion, exertion level).

2.2.3.3 Free Play

In the 1991 book entitled <u>Free Play: Improvisation in Life and Art</u>, Stephen Nachmanovich proposed that free play was the main mechanism through which human's access creativity, both in the arts as well as within life in general[51]. Nachmanovich articulates the implicit wisdom that any successful artist discovers for themselves: to attain the goal of creative inspiration one must suspend focus on the final goal and "play" with the initial conditions present in the moment.

Within the performing arts, we explicitly practice free play as a skill, calling the practice “improvisation” or simply “improv”.

In dance specifically, free play is practiced within movement. Pedagogical techniques of movement improv involve setting a structure and tasking the performer to create, or generate, movement through exploration, or play, within that structure. Dance improv is similar to jazz improv, in which performers explore pitch, rhythm and other elements of musical performance within the structure of a specific song. Within dance improv, movers explore dynamics within specified constraints of space, time, weight and other qualities of movement. A simple dance improv exercise might involve exploring paths of the center of mass from sitting to standing, while a more challenging exercise might require fast, dabbing movement with one arm coincident with slow, carving movement with the contralateral arm.

The concept and practice of improv is ingrained in every dance genre. Even within choreographed dance (e.g., classical ballet) improv is embedded through artistic interpretation during performance. Within ballroom dance, such as forms of foxtrot, waltz, or quickstep, improv is routinely incorporated as “embellishment,” and is a marker of advanced ability within the form. Regardless of form, improvisational generation of movement is ubiquitous in dance practices and the practice might provide an opportunity for persons with neurotrauma to practice movement exploration through free play.

2.2.4 Evidence-Based Design of Interventions

Not all physical trainings are equally effective. This is true regardless of whether participants are elite athletes or attempting to recovery from neurotrauma. To design an effective movement training, it is important to consider current evidence from the motor learning literature about the influence of intervention design choices on training outcomes [2,52,53]. What follows is a partial review of evidence relevant for intervention design.

2.2.4.1 The Constraints-Led Approach

Newell's Theory of Constraints (1986)[54–56] is one prominent theory of motor learning to emerge from the DST school of thought. To date, this theory represents the most concrete application of DST to Neurorehabilitation client care. Often referred to as the constraints-led approach, this theory predicts that motor learning is driven by limitations, or boundary conditions, imposed by three factors: the mover (e.g., what joint mobility/stability is available?), the task being attempted (e.g., does the task require reach and grasp or balance and locomotion?), and the environment (e.g., must the mover reach through air or water?; is the ground surface stable?). While originally proposed as an ecological approach to situate childhood development of motor control within the physics of movement dynamics, Newell and Valvano (1998)[57] as well as Newell and Verhoeven (2017)[55] explicitly extended the Theory of Constraints to explain and guide the recovery of movement after neurotrauma.

2.2.4.2 Movement Dose

Research indicates that the **dose** of repeated activity practice corresponds to central gains in representation of the practiced movement within the CNS, leading to the conclusion that more practice leads to more plasticity[58–60]. Quantity as a mechanism of action for medicinal movement is comparable to the dose of an oral medication one might take to stimulate the desired physiologic response. Just as 200 milligrams (mg) of ibuprofen will reduce inflammation in a healthy adult, some quantifiable dose of movement attempts is presumed to stimulate neuroplastic self-organization of the human system after neurotrauma. While we know that movement in some dose is required, however, the pharmacokinetics and pharmacodynamics of medicinal movement has yet to be systematically defined across the range of neuropathologies for which movement is medicine[61,62]. Hospital-based therapy in the United States (US) has been criticized for promoting far fewer movement attempts than have been shown effective in animal studies of neuroplasticity[62–66]. For the purpose of the work presented in this thesis, I started from the assumption that an increase in quantity of neurosensorimotor training performance was desirable within Neurorehabilitation applications, with no concerns about surpassing a recommended dose of movement therapy.

Another aspect influencing the delivery of movement therapy dose is **timing**. To return to the ibuprofen example, it is important to know when to start, and how often to take, 200mg of ibuprofen to stimulate the desired physiologic effect. Similarly, it is important to know at what point movement therapy should commence and how often a dose should be delivered to stimulate desired neurorecovery. This is particularly true in rehabilitation after neurotrauma, when some delay in commencement of movement therapy may be indicated to allow resolution of the initial trauma, but too much delay risks missing a window of opportunity for neurorecovery[61,62].

2.2.4.3 Movement Design

Research also indicates that certain qualities of movement design mediate positive outcomes. Specifically, to rehabilitate neurosensorimotor skills therapeutic movement should be task-specific and allow for trial-and-error with well-designed feedback about successes and failures.

2.2.4.3.1 Task-Specific Training

Task-specific training strategies are widely applied within Neurorehabilitation[67] to provide contextual conditions and constraints within activity-based training[54,56]. To restore a neurosensorimotor skill one must attempt to perform that skill[56] and task-specific training strategies represent one way for clinicians to craft such targeted activity-based practice[56]. For instance, individuals with disabling conditions affecting walking, balancing, or reaching are guided to practice walking, balancing, or reaching, respectively. We can conceptualize task-specific training as a constraints-led approach to craft activity-based training at the intersection of the patient's existing and desired dynamic control manifold.

2.2.4.3.2 Challenge Point

One model of learning that can help us craft patient-specific training at the intersection of the patient's existing and desired dynamic control manifold is the Challenge Point Framework model of learning, as articulated by Guadagnoli and Lee (2004)[68]. This model extends the constraints-led approach by establishing that: 1) the mover's limitations include skill level; 2) the task's limitations include difficulty level, and 3) skill level of the mover and difficulty level of the task intersect to define the *challenge point*. Because the skill level of the client is developing in the midst of the training, the challenge point must be considered an emergent phenomenon which, ideally, would be tuned in the midst of the training bout to optimize the learning experience[68].

2.2.4.3.3 Trial-and-Error

As for many kinds of learning, skill acquisition involves learning from mistakes[69–71]. To facilitate learning within task-specific training strategies, trial-and-error must be allowed. At the same time, in Neurorehabilitation, injury must be prevented. The client must be allowed to err, and yet must be protected against errors that could lead to harm. Therefore, the supportive clinical environment must encourage risk, yet ensure safety.

2.2.4.3.4 Assistance

Assistance is provided to the client in order to create an environment that encourages risk while ensuring safety. For instance, a client with paralysis who is challenged to stand upright may find that the nature of their injuries precludes the practice of unsupported walking motions. However, if body weight support were provided in the form of an overhead harness, the client could be assisted to practice locomotor function. Therefore, an important consideration in designing movement for task-specific training involves the type of assistance that will be required to facilitate client practice of the target task.

2.2.4.3.5 Feedback

Another aspect of designing movement experiences intended to promote motor learning is feedback about movement performance, which can be presented in various ways. Some different forms of feedback include visual (e.g., mirror images, graphic art), auditory (e.g. verbal, musical), and/or tactile (e.g. clinician touch, sensor vibration). The timing of feedback relative to movement performance varies as well. Feedback experienced simultaneous with performance, (e.g., real-time, digital movement feedback) provides “knowledge of performance” (KP)[72]. Alternately feedback can be provided after completion of performance (e.g., after a basketball is thrown, the mover witnesses whether the ball did or did not land in the basket); for this paradigm, the motor learning literature uses the term “knowledge of results” (KR)[73–76]. Feedback can also inform the mover about correctness or incorrectness of movement performed[77,78]. Or, feedback can be crafted to reinforce the performance of movement without conveying assessment[22,79]. Various combinations of feedback designs have been evaluated with regard to promotion of skill learning among individuals who are cognitively intact[80], however best practices for use of feedback among individuals with combinatorial cognitive and motor deficits remain unclear.

2.2.4.4 Client Attention

Therapeutic response to movement is mediated by the client’s attention to their own movement performance, independent of activity dose delivered. The body of literature investigating client attention to activity-based training indicates that a) client attention to movement performance influences clinically-relevant outcomes, b) some attentional foci are better than others and c) certain initial conditions promote more efficacious attention on the part of the mover (e.g., instruction or opportunity provided before task performance). A partial review of client attentional factors that have been shown to mediate Neurorehabilitation outcomes follows.

2.2.4.4.1 Level of Effort

The Level of Effort (LOE) put forth by the mover has emerged as a powerful mediator of outcomes at discharge from inpatient care[81]. LOE is operationally defined as the patient being attentive and engaged in goal-directed activity, including initiating activity, incorporating clinician feedback, and persevering when activities become challenging[82]. LOE is measured using the Rehabilitation Intensity of Therapy Scale[83], a single item, behaviorally anchored, 7-point scale. A study of 1820 individuals receiving inpatient care for traumatic brain injury (TBI) in 9 different US hospitals, found that patient LOE was a bigger driver of positive outcomes at discharge than therapy dose[81]. However, other aspects of movement quality remain understudied, such as the impact of creative engagement in movement performance.

2.2.4.4.2 Allocentric or External Focus of Attention

The constraints-led approach predicts that an allocentric, external focus of attention (EFA) should support motor learning better than an egocentric, internal focus of attention. This is to say that the tactic of focusing attention outside of one's body on the effects of action or the surrounding environment[80,84,85], rather than reinvesting focus inside the body[86], should shift motor planning into a more optimal state and improve attainment of motor goals. Substantial evidence from healthy populations[84,85,87–91], and some evidence from Neurorehabilitation populations[92,93], supports the hypothesis.

2.2.4.4.3 Autonomy Support

Autonomy support has emerged as an important design consideration for neurosensorimotor skill training protocols because providing opportunities for the client to perceive autonomous control of the experience has been shown to improve outcomes[89,94–96]. Even providing opportunities for seemingly incidental choices about aspects of one's training has been shown to improve outcomes. For instance, healthy study participants demonstrated improved performance on a novel golf put task when allowed to choose the color of the golf ball they were to use during task training[95].

2.2.4.4.4 Cognitive and Motor Deficits Intersect

Neurotrauma often affects anatomical structures involved in cognition and movement, in combination. For this reason, efforts to rehabilitate neuromotor function may be complicated by the presence of cognitive deficits, and vice versa. The client who needs medical therapy to recover physical function (e.g., grasp, standing, walking) may be unable to process verbal instructions or remember a task sequence, thus limiting the ability of the clinician to communicate exercise instruction to their client. The Functional Independence Measure is routinely used in the US within inpatient care to detect and track deficits in cognition and communication[97] and may be used, as in Paper 2, as an indicator of whether a specific client will be likely to understand verbal or non-verbal instructions about task performance. Intervention designs hoping to support task-specific training, tuned to a specific challenge point, require consideration of how to instruct a person with combinatorial cognitive and motor deficits in performance of the desired task.

2.3 CENTRAL QUESTION OF THE THESIS

Previous research has shown that persons with neurotrauma might be able to recover neuromotor control through the mechanism of experience-dependent plasticity[3,26,27] (section 2.2.1.4.3). According to Dynamical Systems Theory (DST; section 2.2.2.2), the negentropic nature of the dynamic system must be leveraged to self-organize around physical stimuli[7] in order to induce such implicit learning after neurotrauma. Operationally, to induce neural restoration clinicians craft task-specific training[12–16] (section 2.2.4.3.1), in keeping with a constraints-led approach[54,56] (section 2.2.4.1). Through this strategy of task-specific training (section 2.2.4.3.1) clients are provided opportunities to practice dynamic movement solutions through trial-and-error (section 2.2.4.3.3).

However, even when best known practices for designing task-specific training are applied, full recovery remains elusive for individuals with neurotrauma in Neurorehabilitation care[14,98]. At least 33% of individuals with TBI show persistent neurosensorimotor deficits two years after injury[98] while 43% of individuals with iSCI experience no measurable improvement in balance and walking function[14]. The data indicate that recovery is available, yet far from universal.

Reports of some recovery after neurotrauma are both hopeful and disappointing. Despite tremendous gains since the discovery of neuroplastic potential, more work is needed to promote more complete recovery for more people. Therefore, I pose the central question of this thesis: **could activity-based training be optimized to further advance functional recovery after neurotrauma?**

Figure 1 diagrams my approach to the central question of the thesis. In order to advance skill learning of the client's dynamical system, the system must be exposed to the dynamic stimuli that we think catalyze skill learning. Delivery of these stimuli is accomplished through task-specific training within Neurorehabilitation. However, both client attention to and dynamic stimuli delivered within the training must be optimized. This is to say that both client attention and dynamic stimuli are necessary inputs to drive remodeling of the dynamic system. My approach to advancing the goal of the thesis is to investigate dance and biomechanics-based approaches to optimizing client attention and dynamic stimuli, respectively.

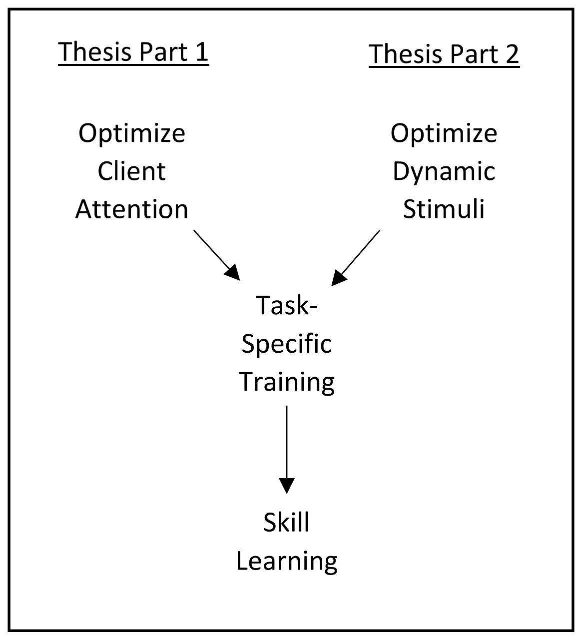

Figure 1: Diagram of approach to the central question of the thesis.

Part 1 of this thesis seeks to motivate client attention to task-specific training through dance-based engagement (Figure 1). Part 2 of this thesis seeks to establish foundational knowledge about the dynamic stimuli associated with task-specific training through biomechanical characterization. Accordingly, Part 1 of the central question of this thesis asks: can dance-based paradigms help to motivate therapeutic movement performance among individuals with intersecting cognitive and motor deficits? Part 2 of the central question of this thesis asks: can we improve basic knowledge about the dynamics of neurologically intact function, building a base of understanding from which to optimize the dynamic stimuli delivered within Neurorehabilitation? While related, Parts 1 and 2 require different background information and research approaches to investigate as explored further in subsequent sections of this thesis.

2.4 INTRODUCTION TO CENTRAL QUESTION PART 1: DANCE-BASED APPROACHES TO ADVANCING SKILL LEARNING WITHIN NEUROREHABILITATION

Clinicians face a dilemma: the success of their plan of care depends on client participation in therapeutic movement performance. The client must be actively engaged in prescribed activity or the clinician's plan of care will fail. The clinician can craft a brilliant evidence-based task-specific training that allows for trial-and-error with evidence-based design of feedback. They may schedule quantity of movement perfectly in terms of both dose and timing. But if the client does not attend to the training during participation, outcomes will suffer. This is particularly difficult when the client has suffered cognitive deficits impairing attention to and understanding of instruction. Could dance-based paradigms represent a novel approach to this dilemma, potentially promoting intrinsic initiation and sustained level of effort in therapeutic movement performance among clients with combinatorial cognitive and motor deficits? Simply put, could dance-based paradigms prompt clients to engage in therapeutic movement, *even if the client cannot cognitively decipher verbal directions about how, exactly, to do the activity*?

There are several ways in which dance-based paradigms might help to motivate therapeutic movement performance among persons with intersecting cognitive and motor deficits. These are explored in Paper 1 of this thesis, a discursive review intended to be accessible to artists, as well as scientists, who are interested in the application of dance for Neurorehabilitation. To summarize concisely, my overriding hypothesis was that dance-based forms of engagement in movement would impact quantity and quality of therapeutic motion dose performance, such that individuals with combinatorial cognitive and motor deficits would actively engage in prescribed motions with focus. Csikszentmihalyi coined the term “flow” for this focused state of autonomous movement performance[99]. I wanted to know if clients with cognitive deficits would a) do the dance-based intervention and b) enter a flow state during therapy that creatively engaged the client in movement performance.

Although the potential of dance-based approaches to impact both quantity and quality of therapeutic activity is clear, such approaches remain largely untapped as a means to motivate patient engagement in neurosensorimotor therapy[79,100]. The art form of music has been studied extensively as a Neurorehabilitation modality, leading to establishment of the Neurologic Music Therapy (NMT)[101] profession. Practicing NMTs learn an array of twenty codified techniques through which music is applied to promote Neurorehabiliation. A gap in knowledge persists, however, regarding the potential for dance-based paradigms to improve quantity and/or quality of Neurorehabilitation training performance. A narrative review of the evidence supporting dance as neurological training follows.

2.4.1 Review of Evidence for Dance as Neurologic Training

Most published studies of dance as a Neurorehabilitation modality focus on dance forms performed to rhythmic music. The use of rhythmic music to accompany some forms of dance may enhance the quality of movement through the neurophenomenon of motor entrainment, as established in the neurologic music therapy (NMT) literature[101]. Dance genres such as Argentine Tango[18,23,25,102–114], Waltz[103,115], Salsa[116,117], Ballet[118–123], Balinese[124], Greek[125–128] improvisation[104,129–134], and others performed to rhythmic music, have been established as feasible and/or efficacious as adjuncts to Neurorehabilitation and/or geriatric treatment.

Within the literature addressing dance to rhythmic music, ballroom dance forms that are social (i.e., involves dancing with a partner) have been studied extensively to engage clients who are aging with and without neurotrauma in a regular movement practice. Six controlled, scientific studies with level 2c evidence or better[135] existed at the outset of the work presented in this thesis[103,105,106,115,116,136]. These 6 studies addressed a variety of neuropathologies using a variety of methodologies. Federici et al (2005) showed that 3 months of salsa dance training improved balance for 20 healthy, older participants (i.e., 58+ years) relative to 20 age-matched, randomly-assigned participants in a passive control group[116]. Similarly, McKinley et al (2008) showed that a cohort of individuals who were older ($\geq$ 62 years) improved functional balance and confidence more through Argentine Tango practice than through a structured walking program. In a randomized trial of participants with stable, chronic heart failure, Belardinelli et al (2008) demonstrated that eight weeks of Waltz practice improved functional capacity and endothelium-dependent dilation at a rate similar to aerobic exercise and better than no exercise[115]. Three studies performed by Hackney et al. firmly established the relevance of social, ballroom dance paradigms within Neurorehabilitation care, demonstrating a positive effect of Argentine Tango[103,105,136] and American Waltz/Foxtrot[103] practice on balance, as measured with the Berg Balance

Scale[137], among individuals with Parkinson Disease. As summarized in Table 1, literature published between 2005 and present (2019) has reported that social, ballroom dance forms might improve neurosensorimotor function for individuals who are aging and/or coping with neurotrauma[18,18,102,107–109,112–114,138].

Table 1: Studies reporting positive effects of partnered dance on balance, organized by population.

Dance Genre	Older Adults	Parkinson	Cancer	Other
Argentine Tango	Hackney et al., 2015a McKinley et al., 2008 Hackney et al., 2015b Hackney et al., 2013	McNeely et al., 2015 Duncan & Earhart, 2014 McKee & Hackney, 2013 Foster et al., 2013 Duncan & Earhart, 2012 Hackney & Earhart, 2010 Hackney & Earhart, 2009 Hackney et al., 2007	Chaudhari et al., 2017b Worthen-Chaudhari et al., *in press*	Dursun et al., 2016 Stroke
Waltz	Belardinelli et al., 2008	Hackney & Earhart, 2009		
Salsa	Federici et al., 2005			Mandelbaum et al., 2016 Multiple Sclerosis

While studies of social, ballroom dance comprise the bulk of literature on dance for health and neural training, other dance art forms such as ballet[118–123] have also received scientific scrutiny as Neurorehabilitation modalities. Houston et al. (2013)[123] and López-Ortiz et al. (2012)[118] established that classical ballet technique was feasible as a physical Neurorehabilitation modality among adults with Parkinson Disease and children with cerebral palsy, respectively. Both research projects demonstrated high adherence and satisfaction with intervention among participants. Additionally, López-Ortiz et al. (2012) reported that clinical stakeholders (i.e., movement therapists) viewed ballet practice as a complementary adjunct to therapy while parents of participants with cerebral palsy perceived therapeutic benefit for their children.

Both ballroom and classical ballet represent traditional forms of dance to rhythmic music. But another, more experimental form of dance to rhythmic music has undergone scientific study as a Neurorehabilitation modality as well: dance improvisation or improv. Pedagogical techniques of dance improv involve setting structural rules of body motion within which the performer explores or plays. Like jazz improv, in which musicians explore elements of performance within a given compositional structure (e.g., melody, rhythm), dance improv involves exploration of motion dynamics within specified constraints in motion composition (e.g. space, time, effort). A simple dance improv exercise might involve exploring, or playing with, different ways to stand from a seated position. A more challenging improv variation could add arm motions to the sit-to-stand exploration. An even more challenging improv variation could require the arms to move differently from each other during the sit-to-stand exploration: perhaps quick, dabbing movement with the left arm coincident with slow, carving movement of the right arm. Improv has been shown feasible as a dance practice for individuals with Parkinson Disease (PD)[129,131–134,142,143] and Alzheimer's Disease (AD)[130] and initial evidence demonstrates a positive impact on health[129,130,133,134]. As of the current date of this thesis, dance improv remains the sole dance form funded for study as a Neurorehabilitation modality through the US-based National Institutes of Health that includes a dancer as Co-Principal Investigator[144].

In summary, many styles of movement to rhythmic music have been shown feasible and/or efficacious for clients of Neurorehabilitation, whether framed as dance or NMT. Three major themes emerge from this literature. First, dance to rhythmic music is feasible for individuals with neurotrauma and neurodegeneration to perform. Second, evidence demonstrates a positive effect of these dance practices on health and balance. Third, this form of activity practice is engaging for clients of Neurorehabilitation, with deficits of many etiologies, as evidenced by high attendance and/or satisfaction reported by all studies in a variety of populations[111,145,146]. A consensus is emerging in the scientific literature that dance-to-music provides an avenue through which to engage individuals with neurotrauma in a regular dose of movement that is therapeutic as an adjunct to their Neurorehabilitation care.

2.4.2 The Gap

Within the growing body of literature addressing dance-to-music dance for Neurorehabilitation training, however, a gap in knowledge persist regarding more contemporary forms of dance. For instance, artistic explorations of motion that do not rely on rhythmic music remain unexplored. While dance to rhythmic music is an important neurologic training option, movement-to-music represents a small sample of the dance genres that might improve quantity and quality of therapy performed by persons with intersecting cognitive and motor deficits.

In particular, the contemporary dance technology medium of interactive art represents a promising innovation through which to transform hospital-based physical Neurorehabilitation training into a creative motion endeavor. While interactive robotics[147] and gaming[148–151] have been studied as

Neurorehabilitation modalities, interactive dance and art technologies remain understudied as a way to motivate client attention to, and voluntary engagement in, therapeutic activity.

Additionally, the arts-based concept of free play or improv remains unexplored as a Neurorehabilitation movement practice. This oversight is particularly concerning given the premise that exploration of free play might be the catalyst for generating novel movement solutions[51]. One explicit goal of Neurorehabilitation is to guide clients to find novel movement solutions, whether through neurorecovery or compensation. If free play is the incubator for creative movement discoveries, then incorporating improv pedagogy within Neurorehabilitation training might support clients to achieve the clinical goal of generating novel movement solutions. The contemporary dance technology medium of Interactive art might solve this disconnect as well, promoting free play with movement inside the bounds of prescribed neurosensorimotor rehabilitation designs.

Finally, at the time of this thesis, no existing dance solution for Neurorehabilitation had addressed, explicitly, relevant aspects of therapeutic movement activity such as feedback design, external focus of attention, and autonomy support. Fields such as neurology and robotics have been criticized for proposing Neurorehabilitation training solutions without apparent consideration of extant motor learning principles[2,52]. In this way, existing literature addressing dance as a neurologic training option had stopped short of evidence-based design as well.

2.4.3 A Proposed Solution

Given the promise of dance-based solutions, I perceived a need to embed the artistic process of movement arts within hospital-based exercise prescription. As both dancer and biomechanist, I have observed free play in movement happening regularly within neurosensorimotor rehabilitation from neurotrauma as clients explore the dynamic manifold of movement remaining to them. I could imagine ways to amplify free play within hospital-based movement therapy using methods and pedagogies from contemporary dance arts that fit existing evidence from motor control.

For my first attempt to address this goal, I turned to dance technology: a genre of interactive art that could provide aesthetically-designed, real-time movement feedback[22,152] during therapy performance. This genre of dance-based, digital art was attractive for many reasons, discussed in more detail in section 2.4.4. Most importantly to me, artistic movement feedback had the potential to engage people with combinatorial motor and cognitive deficits to autonomously explore, or play within, their existing dynamic control manifold. To begin to develop a relevant solution, I started at the Medical Research Council (MRC) stage of Development to design a prototype interactive arts technology that individuals with central nervous system injury could engage as artistic biofeedback for movement therapy. To be successful, the application would need to a) engage individuals with severe cognitive and/or motor deficits in movement therapy performance and b) increase clients' access to known mechanisms of implicit skill learning. A partial rationale follows regarding how artistic feedback might differ from traditional therapy (without digital feedback) or other digital feedback solutions (e.g. games) regarding known mechanisms of implicit skill learning

2.4.4 Relevance for Skill Learning Post-Neurotrauma

The following represents a partial review of mechanisms of skill learning that might be influenced through use of interactive art as augmentative movement feedback.

2.4.4.1 Movement Dose

Dose of neuromotor therapy is known to mediate plasticity (section 2.2.1.7.4), yet the dose of movement therapy administered by US-based hospitals had been criticized as falling far below the doses of activity shown to induce neuroplasticity in animal models[63–65]. Better patient engagement in therapy tasks via interactive gaming had been proposed as one avenue to increase movement dose within hospital-based therapy[153]. However, such games are often inaccessible for clients of Neurorehabilitation because understanding the game mechanics involved requires preserved cognitive function (e.g., strategic thinking, memory) that might not be available to individuals with cognitive deficits. Interactive art represents an alternate genre of digital feedback that individuals with severe cognitive deficits might be able to participate in where gaming or traditional therapy-delivery models fail.

2.4.4.2 Movement Design

Task-specificity is a critical aspect of therapeutic movement design (section 2.2.4.3.1), but it can be tedious for clients of Neurorehabilitation. Interactive art (section 2.2.3.2) may provide a point of focus during repeated performance of a specific task such as kneading Theraputty® or balancing on one-leg. Focus on artistic output during the massed practice required for skill acquisition may prove equally important for clients with intact and impaired cognition.

Feedback about motion performance is an important aspect of therapeutic movement design (section 2.2.4.3.5). Feedback that presents output in the form of abstract graphic art represents a relatively novel paradigm in therapeutic feedback. Artistic feedback provides concrete evidence of work performed without judging whether the work was performed well or poorly. In the creative mode of artmaking there is no lose state. Clients may like or dislike their output, but there is no objective judgement of their performance as good or bad. Paradoxically, this paradigm of “no lose” feedback might support the process of learning through trial-and-error (section 2.2.4.3.3) by removing external definitions of error, thus facilitating intrinsic commitment to trial-and-error attempts that take the form of free play (section 2.2.3.3).

Furthermore, allowing free play within targeted activities might provide a more client-driven model for tuning the challenge point at which movement therapy bouts are performed (section 2.2.4.3.2). If clients are supported to perform their prescribed activity with some tolerance for free play (section 2.2.3.3), theoretically the increased autonomy might enable them to adjust their challenge point independently, as their skill level increases. Additionally, through free play, the client may push themselves to higher levels of skill performance than the clinician thought possible - or more than clinicians were able to explicitly instruct given client cognitive and communication deficits.

2.4.4.3 Client Attention

Interactive art as a form of movement feedback might impact clinical progress through focusing client attention in positive ways. In the case of clients with attention deficits, interactive art may provide a critical way to focus attention on movement therapy performance at all. For clients with brain injuries that preclude following directions, any technique for improving attention could be revolutionary. For clients with low or high cognitive function, framing movement therapy as an internally initiated creative endeavor, rather than an externally directed exercise routine, might increase client level of effort, a factor in inpatient rehabilitation outcomes[81] (section 2.2.4.4.1).

Furthermore, representing movement in real-time as an artistic trace emerging on a screen positioned several feet away from the client might be a simple way to induce an external focus of attention (section 2.2.4.4.2). Attending to one's motion as abstractly, and aesthetically, depicted on a computer screen some distance away should serve to shift attention away from the body and toward the effects of one's actions, inducing an allocentric, external focus of attention that has been shown to be beneficial in some Neurorehabilitation models[92,93].

Finally, client choices made within the interactive art process, including subtle movement choices made in the context of free play or the color palette of artistic output, might provide autonomy support (section 2.2.4.4.3). A client's sense of their own autonomy in physical training has been shown to impact outcomes in unanticipated ways[94–96]. After neurotrauma, individuals may find their autonomy and independence drastically altered; even seemingly incidental opportunities for choice might have powerful training effects[94].

2.4.5 Summary of Central Question Part 1

In summary, I took a constraints-led approach (section 2.2.4.1) to designing artistic movement feedback that might influence factors shown to mediate Neurorehabilitation outcomes (e.g., dose[62] (section 2.2.4.2), LOE[81] (section 2.2.4.4.1)), and that might holistically support other potential mechanisms of action among individuals with neurotrauma (e.g., autonomy (section 2.2.4.4.3), allocentric focus of attention (section 2.2.4.4.2)). At the outset of this work, however, two pragmatic challenges prevented testing of this hypothesis. It remained unknown 1) whether brain and spine injured patients could engage with real-time artistic movement feedback given the nature of their injuries and 2) whether clinicians would use and accept the augmentative solution within the context of a busy hospital ward. To begin to explore the implementation of interactive arts among individuals with neurotrauma, studies of design and feasibility were warranted. Therefore, Aim 1 of this thesis addresses Development, Feasibility, and Implementation within the MRC Model (Figure 2) through two papers. Paper 1 provides a state-of-the-art review of the intersection between motor learning for Neurorehabilitation and specific dance art practices. In addition to this review, Paper 1 reports stakeholder responses to a specific interactive technology, designed as a proof-of-concept prototype, to test

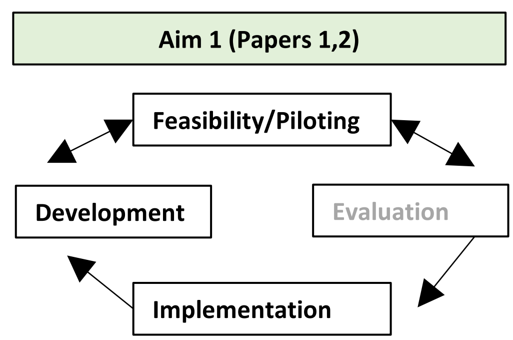

Figure 2: Areas of the MRC Model addressed within Aim 1 are depicted in black text.

application of dance-based approaches to movement education within Neurorehabilitation practice. Paper 2 establishes feasibility of applying the dance-based interactive technology within hospital-based, acute Neurorehabilitation.

2.4.5.1 Limitations of the Work

In an ideal world, to pursue study of Central Question Part 1, I would evaluate the effect of artistic augmentation on efferent signaling through use of electromyographic data acquisition. Furthermore, I would measure movement dynamics using force sensing combined with kinematic measurement; with these two synchronized data sets I could use an inverse dynamics approach to calculate net joint moments and gain rich insight into any changes in movement performance when using artistic movement feedback. Additionally, a controlled test of efficacy remains to be executed, including randomizing patient participants into an active control vs augmented feedback group. Furthermore, such randomized, controlled comparison should be conducted across the continuum of care: from hospital-based to home health care. I currently am writing and submitting grant applications to secure funding for more in depth neural and biomechanical study of central question Part 1 of this thesis. More research is warranted.

2.5 INTRODUCTION TO CENTRAL QUESTION PART 2: BIOMECHANICAL APPROACHES TO ADVANCING SKILL LEARNING WITHIN NEUROREHABILIATION

Clinicians face a dilemma: per DST[7] (section 2.2.1.4.3), the dynamic stimuli delivered within activity-based training drives remodeling of the client's neural system. Despite the critical important of dynamic stimuli for driving neurorecovery, however, optimal dynamics associated with functional recovery have yet to be characterized for the purpose of Neurorehabilitation. To fill the gap in knowledge, a closer biomechanical characterization is required of the dynamic manifold supporting activities such as locomotion and balance. Part 2 of this thesis begins to provide such definition of dynamic stimuli within locomotor (Part 2A) and balance (Part 2B) Neurorehabilitation.

2.5.1 Introduction to Central Question Part 2A: Neurorehabilitation of Locomotor Skill

For individuals with neurotrauma, one way to promote task-specific practice is to attempt to recapitulate the dynamics of normal movement through providing assistance (section 2.2.4.3.4). An example of Neurorehabilitation that adopts this approach is found in the evidence-based training of locomotor function after incomplete spinal cord injury (iSCI).

2.5.2 Evidence-Based Neurorehabilitation of Locomotion after iSCI

Individuals who are unimpaired walk without thinking - literally. They do not need to consciously command one hip to flex while the other extends. The dynamic, inter-joint coordination involved in walking represents an automatic neurophenomenon for those without neural impairment. If this automaticity is lost to neurotrauma such as incomplete spinal cord injury (iSCI), how might Neurorehabilitation restore it? Existing strategies to restore locomotor function after neurotrauma are based on evidence for retained automaticity of stepping function after iSCI under task-specific, submaximal loading conditions[16,154–156], as well as evidence for experience-dependent plasticity in this population[16,157,158].

Best practice to rehabilitate walking function after iSCI is to perform task-specific training (section 2.2.7) that reproduces the phasic load-bearing of walking [16,155,157]. Challenges involved in guiding clients with iSCI to practice walking include safeguarding the client against physical collapse and tuning the challenge point of training to access automaticity in lower extremity function that might be retained post-neurotrauma. These challenges are addressed through providing assistance to the client.

One form of assistance provided is body weight support (BWS), accomplished through suspending the client above a treadmill in either a harness or a robot (e.g., Lokomat®). Applying BWS safeguards against lower extremity collapse while reducing the load on the lower extremity in order to access retained automatic function. Among clients with paralysis, providing support for the torso and upper body during walking training has been found to be beneficial[155,157–160], possibly because such support enables clinicians to control the challenge point (section 2.2.4.3.2) of the walking task.

In one leading paradigm for clients with iSCI, assistance also takes the form of higher treadmill speeds that have been shown to promote muscle activity below the level of the injury[155]. This protocol is called locomotor training (LT) and has demonstrated remarkable ability to induce functional efferent activity in individuals with SCI[154,155,157] through training with human facilitation (vs. robotic facilitation) at speeds above 0.8 m/s (for video of LT published by The Ohio State University Wexner Center see https://www.youtube.com/watch?v=SdOr9g3_Zqc). In addition to activating functional activity of paralyzed muscle within a training bout, LT treadmill training experiences have been proven to result in long-term motor recovery[14,161].

However, at the time of this work, and as reviewed in Papers 3 and 4, there were questions around whether existing BWS treadmill training protocols, such as LT, were fully leveraging recovery potential among participants. Controversy existed, in the literature and in clinical practice, regarding recommended BWS treadmill training parameters for clinicians to employ in order to maximize positive neural reorganization. Some clinician-researchers recommended limiting BWS to no more than 30%[162,163]. Others recommended increasing BWS up to, but not greater than, 50% in order to achieve faster walking speeds and, thus, greater activation of muscles below the level of the injury during practice[155]. The impact of training speed and BWS levels, in combination, on neurorecovery outcomes remained to be systematically investigated.

2.5.3 Biomechanical Studies of BWS Treadmill Training

At the time of the experiment conducted for papers 3 and 4, ten studies had defined the dynamics of healthy walking across some range of BWS levels and treadmill speeds[164–173] (Figure 3). Biomechanical studies had shown that altering speed and BWS during walking changed biomechanical and/or physiologic characteristics[165–167,169,171–173], although changes were non-uniform and varied per LE joint across speed and BWS parameters[168]. These studies, however, varied in ways that hampered translation of knowledge as clinical practice guidelines. Several aspects of study design prevented translation of these biomechanical study results to clinical practice.

To start with, the BWS levels and treadmill speeds that had been studied closely in the biomechanics literature did not align well with those used in clinical practices such as LT. However, no study had yet characterized walking dynamics within the training parameters commonly used in iSCI locomotor rehabilitation:

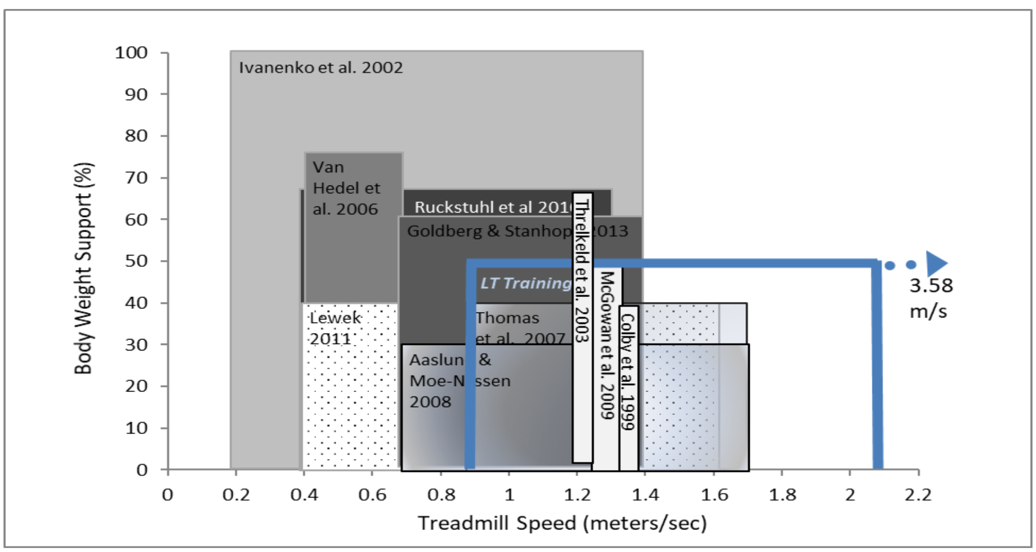

Figure 3: Depiction of training parameters reported in 10 biomechanical studies in comparison to training parameters used clinically in the locomotor training protocol.

≤50% BWS[155,162,163] and speeds ranging from 0.8 meters/second (m/s) to 3.58 m/s[161]. Figure 3 depicts, in grey tones, the range of BWS level and treadmill speed examined per biomechanical study. The range of parameters studied is contrasted against the BWS levels and treadmill speeds used with clients undergoing the LT protocol (depicted in Figure 3 as a thick, blue outline). While there was some overlap between training parameters studied and those used clinically in LT, clinically relevant combinations of higher training speeds (above ~1.4 m/s) with BWS levels up to 50% remained unexplored within the biomechanical literature.

In addition to needing to map the dynamic manifold being used clinically, from a DST perspective, I saw a need to compare the dynamics of typical training to the dynamics required for community ambulation. Neurorehabilitation protocols such as LT sought to return individuals with iSCI to walking about in their communities with no BWS (i.e., community ambulation). Community ambulation had previously been associated with a defined speed threshold: Van Hedel et al. (2009)[174] identified that gait speeds of ≥ 0.44 (0.14) m/s differentiated those who returned to community ambulation from those who remained dependent on a wheelchair for community participation. In contrast, LT was practiced at speeds ≥0.8m/s and BWS levels ≤50%. It was possible that use of higher gait speeds and BWS levels in clinical practice was remodeling the dynamical system to produce force patterns that did not support typical community ambulation speeds post iSCI.

In addition to a lack of systematic characterization of dynamics relevant to clinical practice and community ambulation, biomechanical studies had reported results in terms of different outcome variables (e.g., joint moment, joint power, electromyography). This heterogeneity of outcomes further hampered consolidation of knowledge for the purpose of clinical translation. Within this heterogeneous landscape of biomechanical outcomes reporting, joint power was reported in only one prior paper[164], despite the relevance of this outcome for clinical translation. As discussed in section (2.2.2.2), joint power absorption and generation map directly to a physiologic construct - eccentric and concentric muscle contraction - thus supporting multidisciplinary translation through use of common concepts.

Finally, studies that applied a dynamic walking approach (section 2.2.2.2.3) fell short of complete characterization of the system. Prior biomechanical studies had focused on terminal stance to the exclusion of weight acceptance. Furthermore, prior studies had limited the scope of their reports to a subset of relevant lower extremity joint motions (e.g., ankle alone, sagittal plane alone).

Controversy already existed in the field regarding optimal assistive training parameters for iSCI locomotor rehabilitation (section 2.5.2). I felt that this controversy was attributable, at least in part, to the gap in knowledge regarding impact of clinical training parameters on lower extremity dynamics. There was a need for a systematic examination of the dynamic manifold across the range of training parameters and gait phases relevant to clinical practices such as LT. This examination should apply the dynamic walking framework in a comprehensive manner and report measures that translated well to clinical practice.

2.5.4 The Gap

At the outset of the work presented in this thesis, clinicians did not know what dynamic stimuli they were applying during LT. The choices clinicians made about training assistance (section 2.5.2) (i.e., BWS level and treadmill speed) established the dynamic stimuli each client was repetitively exposed to during training. But we had yet to characterize, systematically, the dynamics created by typically used combinations of BWS and speed within the phases of gait that the dynamic walking approach indicated were critical (i.e., the phases involved in double support including weight acceptance and terminal stance). Furthermore, we were lacking basic information regarding the manifold of coordinated lower extremity joint dynamic function that could be expected to support community ambulation. Finally, in addition to a lack of basic information, we faced challenges around translation of information between biomechanics, motor control, and clinical practice. Due to this aspect of the challenge, the gap involved not just characterizing dynamics relevant to iSCI gait training but also communicating results in a way that would impact motor control theory and clinical care in a meaningful way. I believed that this gap in knowledge hindered clinicians' ability to deliver a targeted, well-designed activity-based training experience.

2.5.5 A Proposed Solution

Given the importance of dynamic stimuli as input to the client's system, I saw a need to define these stimuli at representative points in the manifold within which clinical training was being performed. An experimental biomechanics approach was required to investigate the effect of clinical assistance parameters on dynamics delivered to the client. In addition, a multidisciplinary approach was required in order to translate to clinical practices. Therefore, I built a collaboration with clinician-scientist Prof D. Michele Basso, translational neuroscientist specializing in iSCI rehabilitation and senior author of the resulting work. To begin to fill the gap in knowledge, we chose to start this investigation in a healthy cohort and define dynamics in terms of joint powers, an approach I favored for the purpose of clinical translation (section 2.2.2.3). The proposed solution provides foundational knowledge from which we can begin to advance skill learning among clients with iSCI.

2.5.6 Relevance for Skill Learning Post-Neurotrauma

2.5.6.1 Movement Design

Assistance (section 2.2.4.3.4) plays an influential role in defining the dynamic manifold (section 2.2.2.2.1) within which implicit skill learning (section 2.2.1.4.2) is intended to occur. When assistive training parameters such as BWS and speed are set, so are the dynamics that the client’s system will be exposed to. Therefore, it is critical to characterize the impact of typical assistive parameters on dynamics to begin to evaluate the dynamics being trained by activity-based training paradigms such as BWS treadmill training.

2.5.7 Summary of Central Question Part 2A

In summary, characterizing the solution spaces associated with clinical practices, and examining these relative to the dynamic manifold supporting community ambulation in a healthy cohort, represents a first step toward optimizing movement design of task-specific trainings (section 2.2.4.3.1) such as LT (section 2.2.4.3).

2.5.7.1 Limitations of the Work

One limitation of the work is that we analyzed dynamics of gait performed on a treadmill while the goal of Neurorehabilitation is to restore the client to community ambulation, not treadmill ambulation. This choice was made to match most clinical environments, which – per my clinical collaborators - have limited space and budgets to maintain BWS systems capable of supporting overground gait training. However, walking on a treadmill differs from walking overground in at least two important ways: lack of peripheral optic flow and self-pacing. Studies indicate that treadmill and overground walking are similar enough to justify therapeutic use among individuals with paralysis[15,175–177] although addition of optic flow stimuli has been suggested to be incorporated where possible[178].

2.5.8 Introduction to Central Question Part 2B: Neurorehabilitation of Balance Skill

Balance is another neurosensorimotor skill that may be compromised due to neurotrauma. A variety of disabling conditions impact balance to the point that Neurorehabilitation is indicated, including but not limited to: normal aging, stroke, TBI, SCI, diabetes, and chemotherapy-induced neuropathy (CIN). At the outset of this work, balance deficits were challenging to track over time among individual clients. Current practices worked for group analysis, but longitudinal tracking of individuals required more sensitive assessment and a basic understanding of within-subject variability in postural control dynamics. Innovation was needed to facilitate longitudinal tracking of individual clients of Neurorehabilitation as they improved, maintained, or declined in function.

2.5.9 Evidence-Based Neurorehabilitation of Balance

Sensorimotor training is a promising treatment to remediate balance deficits across the range of pathologies treated in Neurorehabilitation (section 2.2.1.2) [14,66,179,180]. However, assessment of the effect of sensorimotor training interventions can be challenging. Biomechanical measurement may help to overcome some of the challenges associated with longitudinal assessment of balance within research and clinical care.

At the outset of the work presented in this thesis, popular clinical tests of balance in the US included the Berg Balance Scale (BBS)[137], Balance Evaluation Systems Test (mini-BESTest)[181], and Tinetti balance scale (Tinetti)[182]. These clinical tests all involved qualitative or timed assessment of task performance such as stepping over an obstacle or standing in set positions (e.g., with two feet in parallel or tandem, balancing on one leg). Despite demonstrated clinical utility, these popular clinical tests had known limitations. For instance, BBS has been criticized for taking up to 15 minutes to perform[183], for a ceiling effect[183], and for demonstrating high within-subject variability among individuals with iSCI [184].

It is possible that longitudinal assessment of balance control might be improved through use of quantitative, biomechanical measures that are quick and simple to perform. Candidate measures had been reported in the biomechanical literature as early as 1994[185]. The following section summarizes biomechanical measures that had shown clinical relevance at the outset of this work and might be good candidates to advance longitudinal tracking of balance deficits among clients of Neurorehabilitation.

2.5.10 Biomechanical Studies of Balance Neurorehabilitation

Measurement of the center of pressure (COP) during quiet standing tasks, with eyes closed (QEC), represents a good candidate for longitudinal assessment. This task has been shown to be clinically relevant across a wide range of neuropathologies including, but not limited to, detecting postural control deficits in concussion[186,187,187] and CIN[188,189] as well as identifying fall risk in elderly with and without neurologic impairment[137,185]. Indeed, the original validation of the Berg Balance Scale[137] clinical test of balance compared BBS to COP-based measure results.

There are many ways to analyze the COP data collected during the QEC task. At a typical sample rate of 1000Hz, even 30 seconds of data results in 30,000 data points per test. These quantitative data must be analyzed to provide clinically relevant health insights. Traditional measures of postural sway displacement have proven effective to detect risk of fall in the coming year among individuals who are elderly[185,190–192] and to detect changes in neuromotor health associated with neurotoxic chemotherapy[188,189]. Multiple labs have demonstrated that three specific measures provide clinically-meaningful insight: ellipse area of resultant COP excursion (COPa), variability in medial-lateral sway excursion (RMSml), and mean velocity of medial-lateral sway (COPvml))[193]. These three measures represent area, variability, and velocity of sway during the QEC task, respectively.

Reliability of COP-based measures of postural sway displacement during quiet standing, with eyes open and closed, have been established in cohorts without neurological impairment. Studies have reported the number and duration of trials to collect within a session in order to attain acceptable intraclass correlation (ICC>0.9) [194] and generalizability (G-coefficient>0.7) [195]. Other reports have characterized between-day reliability in terms of the standard error of measurement[196]. Such reports of reliability increase confidence that COP-based measures calculated from quiet standing tasks might be suitable for use to assess balance longitudinally within clinical care.

In summary, the literature supports use of a specific task to use for balance assessment: quiet standing with eyes closed (QEC). Furthermore, the literature supports use of specific COP-based measures to detect and track balance behavior of clients in Neurorehabilitation and gerontology care: COPa, RMSml, COPvml. If clinically relevant tests and calculations have been identified, and confidence in the reliability and validity of COP-based measures is established, what is preventing translation of these biomechanical measures to clinical practice?

2.5.11 The Gap

At the outset of the work presented in this thesis, barriers existed preventing use of COP-based balance tests in the clinic. One such barrier involved a gap in knowledge regarding typical day-to-day changes that we should expect to see in healthy postural control. Dynamic COP signals are stochastic or chaotic in nature such that some variability over time is important for healthy function and to be expected. This healthy movement variability can be represented through statistical modeling of within-subject variability (WSV). In order to assess whether an individual has changed beyond what should be considered healthy variability, an estimate of unimpaired WSV is required and must be communicated with the goal of translation to clinical practice.

2.5.12 A Proposed Solution

To fill this gap in knowledge, I led a study to characterize WSV of standing QEC balance in healthy, unimpaired, middle-aged individuals. Based on the precedent set by Silva, Punt, and Johnson (2011), who reported variability in healthy head posture over 7 days[197], I chose to characterize variability in unimpaired balance function over 6 days. The resulting analysis is published as paper 5 and addresses Aim 2 of this thesis by characterizing the dynamic manifold of unimpaired balance function in terms of within-subject variability.

2.5.13 Relevance for Skill Learning Post-Neurotrauma

2.5.13.1 Assessment of Intervention Design

To begin to optimize Neurorehabilitation interventions we must assess whether clients improve through participation. One aspect of advancing the science involves improving assessment of evidence-based intervention designs (section 2.2.4). The experiment conducted for Paper 5 is relevant to implicit learning post-neurotrauma (section 2.2.1.4.2) because it facilitates a shift in thinking about how we assess rehabilitation goals for an individual: from attaining a single dynamics solution, to attaining a manifold of possible solutions that encompasses the boundaries of optimal movement variability (sections 2.2.2.2.1 and 2.2.2.2.2). To be confident that an intervention has induced meaningful neuromotor change for an individual, change must exceed typical, healthy WSV. Without comparing to an estimate of WSV we risk misidentifying normal day-to-day variability as meaningful change in a client's system. Characterizing WSV in balance function enables better assessment of the design choices made to develop novel interventions. Aspects of intervention design that require careful assessment the task-specificity (section 2.2.4.3.1), challenge point (section 2.2.4.3.2), trial-and-error (section 2.2.4.3.3), assistance (section 2.2.4.3.4), and feedback (section 2.2.4.3.5) provided.

2.5.14 Summary of Central Question Part 2B

In summary, to assess the effect of innovative interventions we need to consider typical variability from the human dynamic system. I began to address this gap in the literature by characterizing WSV in clinically-relevant postural control function among healthy individuals over 6 different days[197].

2.5.14.1 Limitations of the Work

This work is limited in that it assesses WSV of healthy individuals. Ideally, we would want to know WSV of the Neurorehabilitation population of interest. In this way, the work represents a first step toward shifting conceptions of Neurorehabilitation assessment toward a DST framework in which training aims to restore optimal movement variability within a dynamic manifold. More research is indicated among populations that receive Neurorehabilitation care for neurosensorimotor deficits.

3 AIMS OF THESIS

3.1 AIM 1: TO ESTABLISH FEASIBILITY OF AUGMENTING MOVEMENT NEUROREHABILITATION WITH ARTISTIC FEEDBACK (PAPERS 1,2).

Specific Aim 1a: To design artistic real-time feedback technology for use in augmenting Neurorehabilitation movement therapy.

Specific Aim 1b: To evaluate feasibility of implementing the augmentative arts technology, designed in Specific Aim 1a, within hospital-based Neurorehabilitation care.

3.2 AIM 2: TO BEGIN TO CHARACTERIZE THE DYNAMIC MANIFOLD UNDERLYING NEUROREHABILITATION FOR LOCOMOTION (PAPERS 3,4) AND BALANCE (PAPER 5).

Specific Aim 2a: To define the weight acceptance phase of unimpaired gait, in terms of joint power absorption and kinematic surrogate markers, at walking speeds relevant for human spinal cord injury Neurorehabilitation.

Specific Aim 2b: To characterize the dynamics of unimpaired gait, in terms of joint power absorption and generation, at walking speeds and body-weight support levels relevant for human spinal cord injury Neurorehabilitation.

Specific Aim 2c: To characterize the dynamics of unimpaired standing balance, in terms of center-of-pressure based measures, by reporting within-subject variability in a specific assessment task relevant for balance Neurorehabilitation.

4 AIM 1: TO EVALUATE FEASIBLITY OF AUGMENTING MOVEMENT NEUREOREHABILITATION WITH ARTISTIC FEEDBACK (PAPERS 1,2).

4.1 NEW PARTNERSHIPS BETWEEN DANCE AND NEUROSCIENCE: EMBEDDING THE ARTS FOR NEURORECOVERY (PAPER 1)

4.1.1 Background and Research Questions

Paper 1 represents the outcome of *Specific Aim 1a:* To design artistic real-time feedback technology for use in augmenting Neurorehabilitation movement therapy. Paper 1 follows the MRC model, addressing *development and piloting* of an interactive arts movement feedback application within an exploratory study that a produced qualitative data results from relevant stakeholders: patients, artists, and clinicians. The paper was published in a special issue of Dance Research Journal that highlighted the emerging field of Dance and Neuroscience.

4.1.2 Methods Used and Main Findings of Paper 1

Through paper 1, I learned several research skills relevant to my current work. Firstly, I learned to lead a state-of-the-art review. Having acted as a co-author for this type of review previously, in 2007[52] and 2010[198], paper 1 represents my first attempt to lead such a research project. Secondly, I learned to produce written communication that united the STEAM disciplines of Science, Technology, Engineering, Arts, and Medicine cohesively for a diverse audience. Thirdly, I incorporated qualitative research methods to advance *Development* and *Piloting* of a complex intervention, after a decade of exclusively performing quantitative research.

The main findings of the state-of-the-art review were that existing motor learning theory supported the use of arts-based movement practices – such as creative movement exploration or improvisation – to drive neurosensorimotor recovery. Specifically, real-time motion feedback that presented an Action Painting aesthetic created a task constraint for individuals with severe motor and/or cognitive deficits. Furthermore, original research reported in the paper established a) the positive response of stakeholders (i.e., patients, artists, and clinicians) to using interactive arts technology during therapeutic movement performance and b) the observation of different patterns of engagement among individuals with (i.e., patients) and without neurotrauma (i.e., artists, clinicians) as depicted in Table 2. In summary, paper 1 established framework and context for the relevance of art theory to the design of complex medical interventions in Neurorehabilitation.

Table 2: Summary of observational and interview data reported in Paper 1, Table 1.

Subjects (n)	Hours observation	Direct observations	Sample quotes
Patients (20 = 9 design + 11 feasibility)	23	Overall responses: positive (23), neutral (1) and negative (0). Report having lost track of time or having 'gone in the zone'. Learn how to operate the gyroscopic mouse by doing. No observable frustration during learning curve. No observable playful phase. Attention seems to shift the minute he/she sees the drawing respond to his/her movement. Stop moving in order to listen to instructions. Alternately, seem to 'tune out' to spoken instructions once have the sensor and can explore for themselves. Make emotionally engaged comments about the resulting images (poignant – 'Looks like a sunset!' – or funny – 'Looks like mardi gras beads. Everybody take your shirts off!').	'Stop talking already and let me do it.' 'I couldn't even use crayons before, but look what I made.' 'I did that – do you see? I didn't think I could move that shoulder at all but I just drew that.' 'Can I do the computer thing again tomorrow? I'll get up early for it.' 'I really feel like I need this – when can I take it home to work with?' 'Can I take a copy of my drawing home to my [daughter, son, wife, husband, sister-in-law]? I can't believe I made this.'
Artists (9)	6	Demonstrate two responses: before and after gaining physical understanding of how to manipulate sensor to effect drawing. Overall response before: positive (5), neutral (3), negative (1) Overall response after: positive (9). Cycle between committed focus and frustration until learn to manipulate sensor.	'Can I use it on my [leg, foot, torso]? I want to see what kind of drawing a [battement, développé, Limon warm up sequence] makes.' 'Whoa – that did not move the way I expected. Makes me a little nauseous.' 'Can I use this for my own training?'

Subjects (n)	Hours observation	Direct observations	Sample quotes
		Engagement once figure out how to manipulate sensor. Quick to ask for help regarding how to control sensor. Once reach level of comfort, become playful. Wide range of movement qualities explored once in playful phase.	'How are you going to teach patients to use the sensor? You'll need to give them explicit instructions.' 'I think you're on to something. This is really interesting.' 'How fun!'
Clinicians (10)	6	Overall response: positive (10). Generally, once figure out how to manipulate drawing, then hand sensor back and stop using. One clinician, a recreation therapist, demonstrated a playful phase. Clinicians tended to participate more by observing other participants. In several cases, clinicians watched from across the room as patients worked with the programme and then offered their observations of these sessions using the programme. Frequent comments on quality and length of patient attention when the arts-generation programme was in use in contrast to previous training sessions without.	'Oh wow – I get it! Can I use this to do [specific motor goal such as reaching, balancing, walking]?' 'I could really use this to work with patients on [quality of motion such as smoothness, range, speed].' 'My patients are going to love this!' 'Can I use it with my patients now?' 'I need to know how to calibrate so that I can compare movement qualities from session to session.' 'Can we print the images out for patients at the end of their sessions so that they have evidence of their work?' 'That's the longest I've seen [patient] practice in one sitting. And they were more focused on their performance than normal, too.' 'I'd never heard [that patient's] laugh before. What a great sound!'

4.2 A FEASIBLITY STUDY USING INTERACTIVE GRAPHIC ART FEEDBACK TO AUGMENT ACUTE NEUROREHABILITATION THERAPY (PAPER 2)

4.2.1 Background and Research Questions

Paper 2 addresses *Specific Aim 1b:* To evaluate feasibility of the augmentative arts technology, designed in Specific Aim 1a, within hospital-based Neurorehabilitation care. I designed the study reported in Paper 2 in order to assess the *Feasibility* of *Implementing* the ideas and prototype from Paper 1 within acute, inpatient, movement Neurorehabilitation. I hypothesized that the Neurorehabilitation arts technology prototype would be used and accepted in acute Neurorehabilitation by a) patients with severe cognitive and/or motor deficits that complicated their ability to follow explicitly articulated verbal instructions and b) clinicians treating such patients within a busy hospital setting. In addition, I asked the research question: what patient-centered outcomes (Patient-Centered Outcomes Research Institute (PCORI) Methodology Committee, 2014) could be identified to guide future Neurorehabilitation intervention design?

4.2.2 Methods Used and Main Findings of Paper 2

Through Paper 2 I furthered the following research skills relevant to my current work. Firstly, I applied qualitative methods again in a mixed methods design that combined qualitative methods of direct observation with clinical outcomes (e.g., Functional Independence Measure[97]), technology assessment outcomes (e.g., The Unified Theory of Use and Acceptance of Technology questionnaire (UTAUT)[201]), and basic quantitative measures of physical performance (e.g., time for technology set up, duration of patient engagement with technology per activity bout, maximum file size of sensor data recorded per activity bout). As a second research skill that is highly relevant to my current work, I built collaborative relationships with leaders and practitioners within local Neurorehabilitation services for the purpose of advancing research. These relationships were critical to data collection conducted during delivery of billable medical services.

As a third research skill, within this paper I learned to analyze and report data regarding Patient-Centered Outcomes (PCO). Development of this skill is notable because it is a relatively new concept for American biomedical researchers, although it has been apparent in the work of European biomedical researchers such as Professor E. Diane Playford as early as 2007[202,203]. Explicit consideration of the point of view of the individuals being studied (i.e., the client of medicine or “patient”) only became a mainstream expectation in the US after passage of the Affordable Care Act, signed into law by President Obama on March 3, 2010. Logistically, the ACA resulted in creation of the Patient-Centered Outcome Research Institute (PCORI) as a research funding agency. Explicit attention to PCOs within research plans became a prerequisite for scoring well in the PCORI funding process. To be clear about what PCO meant, PCORI collaborated with relevant stakeholders to define the term and posted results in 2014 on the PCORI website[200]. Although Paper 2 of this thesis was published in 2013 - before the 2014 paper defining the term by PCORI - the outcomes reported in Paper 2 are an early example of what has become known as PCOs in US-based Neurorehabilitation research (Note: “patient-centered” outcomes are referred to as “patient-reported” outcomes in paper 2).

The main findings of paper 2 were as follows. Firstly, we reported feasibility of interactive art technology use to augment billable Neurorehabilitation services by a) patients with severe cognitive and motor deficits (Table 3) and b) clinicians from different therapeutic disciplines (Table 4). Secondly, we reported for the first time that patients self-identified that they wanted help to a) perform challenging work for longer periods of time, b) achieve a "flow" state during therapy performance, and c) document work performed in a manner they could see for themselves and show to loved ones (see section 3.1, Paper 2). Thirdly, although we did not measure a control group, qualitative data from this single group study showed that the interactive arts prototype assisted patients to achieve a flow state of engaged, focused attention, even when cognitive and/or motor deficits were severe.

Table 3: Participant data including: Functional Independence Measure (FIM) mean subsection (activities of daily living (ADL), mobility and transfers (M/T), cognition and communication (C/C)) item scores at administration; number of augmented therapy sessions engaged in; length (minutes) of the longest therapeutic activity file recorded. Data reported in Paper 2, Table 1.

Subject	FIM scores section means			FIM scores C/C items					EA use	Data file length
	ADL	M/T	C/C	Comprehension	Expression	Interaction	Problem solving	Memory	# sessions using interactive arts technology	minutes
01	1.5	1.0	5.8	6	6	6	5	6	3	6.0
02	1.0	1.0	2.2	4	1	2	2	2	1	2.8
03	2.7	2.6	4.4	5	5	5	3	4	7	1.4
04	3.3	2.6	4.6	5	4	6	4	4	2	3.0
05	1.0	1.0	4.6	5	5	4	5	4	1	1.4
06	2.2	4.0	3.0	4	4	3	2	2	2	7.3
07	2.2	0.8	4.2	5	5	4	4	3	1	1.2
08	2.8	1.6	4.8	6	4	5	4	5	1	2.6
09	2.3	1.8	4.8	5	5	5	4	5	2	14.4
10	2.5	1.6	4.4	5	3	6	3	5	3	6.3
11	4.0	4.6	3.4	4	4	3	3	3	5	4.9
12	1.5	1.0	3.2	4	3	3	3	3	2	8.8
13	1.2	1.6	3.0	4	2	3	2	4	7	20.1
14	1.8	1.0	4.6	6	5	6	3	3	1	4.0
15	3.5	2.6	3.8	5	4	4	4	2	3	12.0
16	4.7	3.6	4.4	4	5	5	5	3	3	30.3
17	4.3	2.4	4.2	5	6	5	1	4	2	26.3
18	1.0	1.2	1.6	2	1	2	1	2	1	19.3
19	5.2	5.0	6.4	6	7	7	6	6	1	2.3
20	3.8	3.2	5.0	6	4	7	5	3	1	10.4
21	5.2	4.2	3.8	4	4	3	5	3	3	21.6
Mean	**2.7**	**2.3**	**4.1**	**4.8**	**4.1**	**4.5**	**3.5**	**3.6**	**2.5**	**9.8**
SD	**1.4**	**1.3**	**1.1**	**1.0**	**1.5**	**1.5**	**1.4**	**1.2**	**1.8**	**8.8**
Min	**1.0**	**0.8**	**1.6**	**2**	**1**	**2**	**1**	**2**	**1**	**1.2**
Max	**5.2**	**5.0**	**6.4**	**6**	**7**	**7**	**6**	**6**	**7**	**30.3**

Table 4: Exercises performed during acute Neurorehabilitation therapy augmented by interactive arts technology. The following data are reported per exercise: sensor position, therapeutic specialty for which the exercise was performed (physical therapy (PT), occupational therapy (OT), or recreational therapy (TR)), and type of feedback shown to the patient (knowledge of results (KR) or knowledge of performance (KP)). Data reported in Paper 2, Table3.

Exercise performed	Sensor position*	Therapy specialty	Graphic art feedback
Cursive letter formation	Hand (held)	TR	KR, KP
Biceps curls	Forearm	TR	KR, KP
Hip abduction ± theraband	Thigh	TR	KR, KP
Therapeutic drawing	Hand (held)	TR	KR, KP
Kneading Theraputty™	Forearm	TR	KR, KP
Bouncing basketball	Upper Arm	TR	KR
Controlled reaching	Forearm, Hand (held)	OT	KR, KP
Forearm pronation/supination	Forearm	OT	KR, KP
Sorting objects	Upper Arm, Forearm	OT	KR
Folding laundry ± added weight	Upper Arm	OT	KR
Placing objects in a cabinet	Upper Arm	OT	KR
Connecting pieces of piping	Upper Arm, Forearm, Shoulder	OT	KR
Cooking a grilled cheese sandwich	Forearm	OT	KR
Medication management	Forearm	OT	KR
Playing cards	Forearm	OT	KR
Static and dynamic balance ± foam cushion ± torso rotations	Torso	PT	KR, KP
Unilateral standing balance	Torso	PT	KR, KP
Mini-squats	Torso, thigh	PT	KR
Sit-to-stand transfers	Torso	PT	KR
Core Stability exercises on theraball	Torso	PT	KR
Walking ± high knee raises	Torso, Thigh	PT	KR, KP
Dynamic standing proprioceptive neuromuscular facilitation patterns with trunk rotation	Torso	PT	KR
Stepping up/down from platform to front or side	Torso, Thigh	PT	KR, KP
Cervical spine active range of motion	Head	PT	KR, KP

*Strapped to body part with sling unless otherwise noted.

4.3 CONCLUSION OF AIM 1 (PAPERS 1,2)

In summary, through Papers 1 and 2, I demonstrated the feasibility of implementing artistic movement feedback within hospital-based Neurorehabilitation treatment for motor deficits. Thus Aim 1 of this thesis was achieved. Critical findings include that the artistic feedback was feasible for individuals with severe cognitive and motor deficits to engage with, demonstrating the relevance of artistic engagement for this hard-to-reach population. Furthermore, clinical stakeholders reported high use and acceptance of the augmentative solution, providing proof-of-concept that the solution was feasible for use in hospital-based medicine. Finally, the augmentative feedback may have helped patients performing movement therapy to achieve a flow state, an intensely focused mental state of intrinsic motivation and high engagement[204]. Future research aims to characterize the effect of arts feedback on therapeutic movement performance more closely and quantitatively (i.e., movement dynamics).

5 AIM 2: TO BEGIN TO CHARACTERIZE THE DYNAMIC MANIFOLD UNDERLYING NEUROREHABILITATION FOR LOCOMOTION (papers 3,4) AND BALANCE (paper 5).

5.1 A NEW LOOK AT AN OLD PROBLEM: DEFINING WEIGHT ACCCEPTANCE IN HUMAN WALKING (PAPER 3)

5.1.1 Background and Research Questions

Paper 3 sought to address *Specific Aim 2a:* To define the weight acceptance phase of unimpaired gait in terms of joint power absorption and kinematic surrogate markers. We focused on power absorption as a kinetic measure of eccentric motor control function, a previously understudied area of gait rehabilitation. In this paper, we redefined the loading response, or weight acceptance (WA) phase, of the gait cycle in the human model in a manner that translated to existing animal research and that could be applied across the range of walking speeds relevant to human Neurorehabilitation.

5.1.2 Methods Used and Main Findings of Paper 3

In Paper 3, I returned to quantitative research methods to calculate lower extremity (LE) joint power absorption during the WA phase of human walking. We found that existing kinematic definitions from the animal and human literature failed to delineate adequately the kinetics underlying the WA phase of bipedal gait (Figure 4). Based on statistical analysis of our data, we proposed a novel definition for the end of WA within human locomotion. In addition to facilitating translation from animal to human models of gait, this paper supplies new basic evidence suggesting that the inter-joint coordination of LE kinetics during walking is speed specific. Thus, the speeds clinicians chose for patients during practice of locomotion might matter for rehabilitation of both eccentric function and inter-joint coordination.

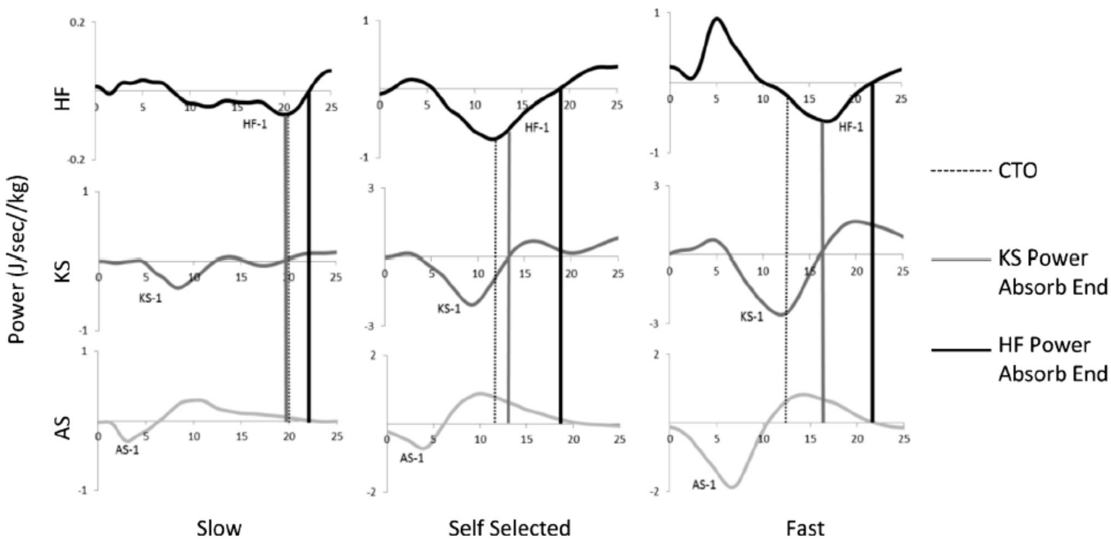

Figure 4: Lower extremity joint powers – sagittal ankle (AS), sagittal knee (KS), and frontal hip (HF) – for one representative subject walking at three speeds (note: representative trials shown). Contralateral toe off (CTO) event is indicated to demonstrate performance of CTO as the marker of power absorption end across speeds. Data reported in Paper 3, Figure 1.

5.2 TRAINING CONDITIONS THAT BEST REPRODUCE THE JOINT POWERS OF UNSUPPORTED WALKING (PAPER 4)

5.2.1 Background and Research Questions

Paper 4 addressed *Specific Aim 2b:* To characterize the dynamics manifold of unimpaired gait, in terms of joint power absorption and generation, at walking speeds and body-weight support levels relevant for human spinal cord injury rehabilitation. Paper 4 extended the findings of Paper 3, characterizing joint power generation as well as absorption, analyzing the end of stance (i.e., propelling phase (PR)) as well as the beginning (i.e., WA phase), and analyzing the effect of body weight support (BWS) as well as speed. In this paper, we demonstrated how training parameters used clinically within BWS treadmill training protocols, specifically walking speed and BWS levels, systematically impacted joint power responses in an unimpaired cohort. We drew from these results to map potential repercussions of clinical parameter choices on joint power variables relevant to training.

5.2.2 Methods Used and Main Findings of Paper 4

In paper 4, I applied traditional biomechanical measures to provide new insight about the manifold within which the kinetics of successful locomotion were preserved when using assistive Neurorehabilitation techniques such as BWS. Our hypothesis was confirmed: LE joint power generation and absorption were better preserved with BWS increases than with treadmill speed increases. There were immediate implications for these findings given that some popular locomotor training protocols advocated for training at fast treadmill speeds and low BWS levels, a combination of assistive techniques that our data indicated might poorly replicate the kinetics of independent walking at community ambulation speeds.

Findings relevant to complex BWS treadmill training intervention design are reproduced from Paper 4 in Figure 5 below. To read Figure 5, first identify the “speed goal” for the patient in the short-term plan of care (i.e., the explicit Neurorehabilitation goal of locomotion at speeds the individual might be capable of attaining independently within a month or so of focused rehabilitation). For most patients entering Neurorehabilitation, the speed goal is slow walking (i.e., $\leq$ 0.8 m/s) performed independently (i.e., with 0% BWS). The slow speed goal is depicted in Figure 5, Block A, lower left corner. Once oriented in Block A, examine the impact of parameters manipulated within BWS treadmill training (i.e., BWS and speed). The effects of increasing speed are represented to the right of the speed goal while the effects of increasing BWS are represented above the speed goal. Combinations of BWS and speed are filled in within the Block A color map. The map breaks detail out further, representing magnitude vs. timing of peak joint powers per LE joint (i.e. hip, knee, ankle) and plane of motion (i.e. sagittal or frontal). This complexity, while relevant, can be overwhelming for those seeking practical guidance. Therefore, for those looking to use the map for point-of-care decisions, we assigned +++ ratings to the parameter combinations that best replicated the kinetics of the speed goal. In the case of Block A, walking at slow speeds with BWS best reproduced the kinetics of the speed goal while increasing speed interfered with replication.

Figure 5: Color map depicting the effect on joint powers when BWS and speed were parametrically varied. Differences in power magnitude and timing of the sagittal hip (HS), frontal hip (HF), sagittal knee (KS), and sagittal ankle (AS) are depicted for WA-, PR-, PR+ (i.e., power absorption in weight acceptance, power absorption in propulsion, and power generation in propulsion). +++ indicates best fit meaning that all variables examined matched the speed goal; ++ indicates that all but 1 or 2 variables matched; + indicates that all but 3 or 4 variables matched.

5.3 CHARACTERIZING WITHIN-SUBJECT VARIABILITY IN QUANTIFIED MEASURES OF BALANCCE CONTROL: A COHORT STUDY (PAPER 5)

5.3.1 Background and Research Questions

Paper 5 addressed *Specific Aim 2c:* To characterize the dynamic manifold of postural control in terms of unimpaired within-subject variability. We posed the research question: What is the variability that can be expected in unimpaired postural control over 3+ days?

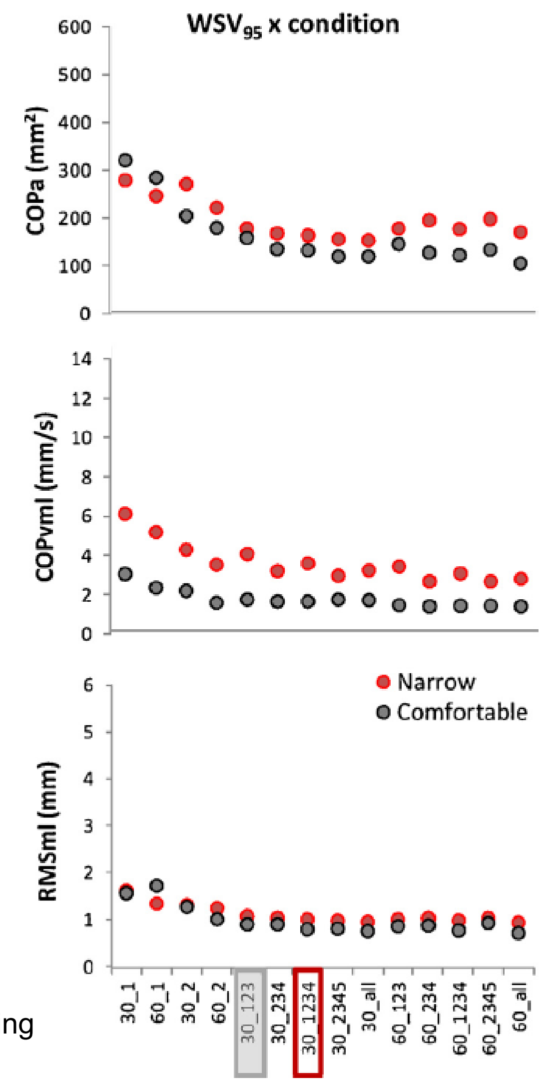

Figure 6: WSV at the 95% confidence interval for 3 center-of-pressure (COP) variables previously found to represent neuromotor health (COPa, COPvml, RMSml) and 2 stances previously reported in the literature (narrow and comfortable).

5.3.2 Methods Used and Main Findings of Paper 5

In paper 5, I learned to address the continuum between carefully controlled research work and real-world implementation at the Neurorehabilitation point-of-care. Using a repeated-measures design we applied a linear mixed model to estimate WSV for specific center-of-pressure (CoP) measures that previously indicated neuromotor health in a variety of populations. We present these data in figure form (as reproduced in Figure 6) as well as in a look up table that clinicians can use at the point of care.

5.4 CONCLUSION OF AIM 2 (PAPERS 3-5)

In conclusion, through these papers I contributed foundational evidence to the literature regarding the dynamic manifold that supports healthy human walking and balance dynamics. To understand the importance of these papers, it is helpful to consider the disconnect that existed previously between clinical practice and biomechanical measurement of the patient experience. All three papers discuss examples of this disconnect and provide empirical data to remedy the gap in knowledge. Finally, all three papers serve to demystify the physics of locomotion and balance, providing concrete guidance for Neurorehabilitation clinicians regarding design and assessment of training regimes.

6 DISCUSSION

6.1 CONTRIBUTION TO THE LITERATURE

These papers fill gaps in fundamental knowledge about supporting the bridging of Neurorehabilitation treatments to arts processes (Aim 1) and biomechanical characterization (Aim 2). The papers advance Neurorehabilitation through an empirical research approach and multidisciplinary lens. The approach of crafting training experiences to support exploration at the intersection of their remaining function and the healthy, dynamic manifold has been fruitful. Intriguing research findings have emerged as interventions developed based on these 5 papers have advanced into Evaluation and Implementation phases of the MRC Model.

With regard to the line of research established in Papers 1 and 2, the overt use of arts theories and practices within medical care, preliminary findings indicate that outpatients treated for balance deficits improved more when performing physiotherapy with the art technology modality than when performing physiotherapy alone[20]. In terms of thought leadership, this work is foundational for the interdisciplinary field of Dance and Neurorehabilitation. Based on my work in this emergent field, I was tasked with representing Dance and Neuroscience for the past 2 years on the Executive Committee of the Arts and Neuroscience Interest Group of the American College of Rehabilitation Medicine, an organization with international reach.

Papers 3 and 4 represent a less overt application of dance practices to rehabilitation. Nevertheless, I brought a dancer's sensibility to the hypotheses that we could improve neurorecovery by a) training eccentric control to promote mastery of skill and b) characterizing the manifold of successful walking function given defined assistance. My interest in this work stemmed from early observations that walking rehabilitation often reversed the "plie" action (i.e., closed-chain, eccentric knee flexion) performed in typical gait during the WA phase. Existing strategies seemed to favor a lower extremity coordination during WA that locked the stance knee in terminal extension and the stance hip into a narrow range of mechanical play in the frontal plane. This strategy effectively reduces the degrees of freedom such that the LE acts as a mechanical strut during loading response. A strut is an excellent compensation to stabilize the body in stance. However, from the dynamic walking perspective[41], I had hypothesized that the strategy, by limiting degrees of freedom, had also limited the magnitude of deceleration that the LE could handle during loading response, thus effectively limiting the gait speeds attainable by the patient. We wrote Papers 3 and 4 to support further study of these hypotheses in the human model. Building from Dr. Basso's extensive study of eccentric function post iSCI in an animal model, as well as on our joint work in Papers 3 and 4, our team went on to evaluate the effect of a BWS training strategy that targeted eccentric function in the lower extremity during the WA phase of walking. Through biomechanical and imaging data we confirmed success of eccentrically-targeted training with regard to functional recovery and central plasticity among individuals with iSCI who had previously been discharged from existing BSWTT treatments for having attained their highest level of recovery believed possible[9,17,19].

Paper 5 extends the line of research established in Papers 3 and 4 and was also designed from my perspective as dancer and biomechanist. In dance, you have good days and bad days - when you can or can't perfect a choreographed move; and we are experienced in the idea that true mastery of a move or skill often takes a non-linear path[205]. I hypothesized that this typical WSV would be quantifiable in a manner that advanced longitudinal tracking of individuals with neurotrauma. Paper 5 quantified unimpaired movement variability in postural control as a reference for clinicians seeking to shift their client's performance by a margin that exceeded healthy WSV. This paper provides a critical reference for assessment of novel interventions designed to improve postural control among individuals with neurotrauma[18,20,23,24,145].

In terms of the practical reality of funding a research trajectory, all five papers have set the stage for continued financial support through federal grant funding and/or intellectual property commercialization. Papers 1 and 2 led to commercialization of the design prototype through The Ohio State University (see Rekovo.com). The methodological skills learned in papers 1 and 2 enabled me to secure funding for study of a new implicit skill learning paradigm – symptom management after concussion – including completion of NIH grant R43HD075638 (clinicialtrials.gov identifier NCT01398566) and resulting publications [206]. Papers 3 and 4 positioned our team to secure two grants from the NIH and the Craig H. Neilson Foundation (NIH R21 HD082808 and CHNF #316282, respectively) to evaluate the effect of BWS treadmill training designed to target the manifold within which our data said the patient would be best positioned to recover lower extremity eccentric function (PI: Basso, Co-Is: Worthen-Chaudhari, Schmiedeler). Finally, paper 5 set the stage for investigations of balance interventions in TBI, supported by two grant funding mechanisms: a) Mechanism: OSU Chronic Brain Injury Pilot Grant (PI: LWC) and b) Mechanism: Industry-funded study of Neuromodulation for TBI (PI: Dr. William Pease).

6.2 CLINICAL IMPLICATIONS

The work presented in this thesis has real-world clinical implications: the outcomes we seek through explicit goal-setting[207–212] require implicit process to accomplish. However, novel avenues are available to access and rehabilitate prelinguistic intelligence of clients who have experienced neurotrauma. Science, Technology, Engineering, and Medicine may have to revisit Art for research and development of these novel avenues, but this thesis provides one demonstration of how STEM might take a STEAM approach to solving problems facing humanity.

6.3 LESSONS LEARNED FROM THE PUBLISHED WORK

In publishing these 5 papers, I learned much about how I might have executed the research better. This list of lessons learned is long. In addition to previous sections discussing Limitations of the Work (sections 2.4.5.1, 2.5.7.1, and 2.5.14.1), below, I highlight lessons learned and summarize limitations of the work.

Overall, I learned much about conducting ecologically valid research, in real-world settings, without getting in the way of the staff and patients who make the setting ecologically valid. My fieldwork within billable, medical services was critical to design and execution of papers 1-5 but took some work to get right. Ultimately, I turned to ethnographic research methods for hospital settings[213], adopting the approach of “negotiated interactive observation”[214]. Wind (2008) aptly describes research fieldwork within medical care settings as having “the potential to unsettle a delicate relationship between patient and health care staff and to cast judgement over the care given” (Wind 2008, p. 84). To begin to conduct ecologically valid research about medical care, I had to recognize that my presence, as a researcher, was not passive. My very presence impacted “critical dialogical relationships with the people we study” (Wind 2008, p. 87). I had not grappled with this aspect of conducting research in medicine prior to the papers presented in this thesis.

In addition to my own learning curve regarding how best to negotiate interactive observations within Dodd Rehabilitation Hospital, I also need to teach the concept of negotiated interactive observation to others. Such as students who sought to work with me. Or to grant and manuscript reviewers who sometimes prioritize complicated biomechanical analyses over ecologically valid fieldwork. Sometimes the science is best advanced by exhaustive motion capture methods that require participants with disability to wear a bathing suit and reflective markers for 3-4 hours while attempting to walk or sit or stand to fatigue in a biomechanics laboratory. Other times, the science is best advanced in the field, by collecting 30 seconds of postural control data while participants wait for regularly scheduled medical appointments. Whether regarding students or reviewers, communication of this approach to fieldwork in medical settings is critical to advancing my research program. I continue to build skills around effectively communicating the relevance of ethnographic research methods for impactful biomedical innovation.

In addition, I learned that reports of feasibility, such as represented by Paper 2, can be difficult to publish in the US. Despite the importance of feasibility testing for development of complex interventions, as evidenced by inclusion of this scope of work in the MRC guidelines, a finding of feasibility is rarely considered noteworthy or suitable for publication in US-based scientific journals. The amount of time and resources required to establish feasibility of a novel approach is disproportionate to number of published papers resulting from the effort. Paper 2 was publishable as a feasibility study in the medical journal, NeuroRehabilitation, because the application of art theory to a Neurorehabilitation intervention was highly novel. In contrast, another funded project to gamify CIMT took years to publish as a feasibility study[215] despite the importance of the idea to advance client access to evidence-based rehabilitation medicine. After publishing Paper 2, I honed my strategy regarding feasibility testing. I started figuring out how to finance the collection of controlled comparison data during feasibility testing. For instance, in 2014 I secured funding from the NIH to evaluate the feasibility of augmenting medical care of persistent concussion symptoms through client use of a social, health app. To secure funding as a Phase I study of feasibility, I defined Aims that did not reference a control group. To publish the study, we went ahead and collected a control group[206]. This stretching of research scope and budgets has not been possible with all subsequent research projects, but it is now a defined goal for my lab.

Finally, I learned to apply a human rights perspective within Neurorehabilitation research. Siegert, Ward, and Playford (2010) introduce a human right perspective to health care in their paper “Human rights and rehabilitation outcomes”[203]. They argue that human rights and public health are inseparable and discuss impact of this assertion for individuals whose lives have been interrupted by neurotrauma. The perspective they outline has implications for research as well as care within Neurorehabilitation. As a researcher, I can be within the terms of a human subject’s research consent document, without truly prioritizing the dignity of the individuals I seek to study. Consenting to participate in research does not obviate an individual’s right to dignity in the form of: personal freedom, material subsistence, personal security, elemental equality, and/or social recognition[216]. This is a lesson that I knew, in concept, at the start of the studies presented in this thesis. But it is a lesson I had to consider from many different, unexpected angles as I conducted this research and all subsequent research. I continue to grow in my understanding of how best to respect and credit the stakeholders who participate in research that I design.

While results of the experiments presented in this thesis have been published in prestigious journals, no published work is perfect and there are aspects of each study that I would do differently today. For example, I should have used the Rehabilitation Intensity of Therapy Scale[81,82] to assess participant Level of Effort within the experiments conducted for papers 1 and 2. In addition, by simplifying client attention to movement dose and qualitative observation within these experiments I missed an opportunity to identify mechanisms underlying engagement of client's with brain injury. I wish that I had found a way to evaluate client attention explicitly through measures such as electroencephalography, functional near-infrared spectroscopy, eye tracking, and validated psychological outcome measures addressing attention among individuals with TBI. Finally, within the experiment underlying Paper 2, I wish that I had found a way to collect active control data as a comparison as well as an explicit measure of participant satisfaction with intervention that had been validated for use among individuals with severe brain injury. Different decisions in my approach to the experiments underlying papers 1 and 2 would have resulted in a richer answer to central question Part 1 of this thesis.

Similarly, my inquiry into Part 2 of this thesis would have benefited from some different decisions within papers 3-5. For example, in conducting the experiments underlying Papers 3 and 4, I could have collected unimpaired walking dynamics at 0.44m/s, the threshold for community ambulation post iSCI[174]. Dynamics of walking at this speed, collected from a healthy cohort, would have seeded a normative database from which to study the threshold speed for community ambulation post-iSCI. Such a normative database would support investigation of the transition between stepping and continuous, automatic walking function. Also, within the writing of Papers 3 and 4, I wish that I had found a way to incorporate the theoretical construct of the dynamic walking approach[41,42]. Attempts to do so were cut due to strict citation and word limits for the target journal (Gait & Posture) but I feel the papers would be stronger if I had found a way to preserve the reference. In conducting the experiment underlying Paper 5, I could have required a better gender balance, rather than concluding the experiment while the cohort included more women than men. Finally, within my analysis of Paper 5, I wish that I had included non-linear analysis methods, such as sample entropy [217], as variables of interest in addition to traditional COP measures. Inclusion of these elements would have strengthened resulting work.

7 FUTURE RESEARCH QUESTIONS ARISING FROM THE STUDIES

7.1 BRIDGING THE DISCIPLINES

The papers presented in this thesis represent foundational work to augment Neurorehabilitation training through arts-based practices and study of quantified, biomechanical measurement. From these foundations, future research will bridge between the arts and biomechanics by studying arts-based interventions using biomechanical outcome measures. Specifically, I hope to investigate whether creative engagement in a motor learning endeavor might mediate the learning process on a neurophysiologic level, beyond the effects one would expect to see due to increase dose and level of effort. Initial evidence from other labs indicates that creative engagement in movement might prompt structural and/or functional central adaptations in motor planning[129,218], working memory[218], and neural system integration[129,130]. There are many creative engagement strategies from dance pedagogy that have potential to drive such adaptations. I elaborate here on two such strategies: promotion of an artistic performance quality and practice of improvisational movement generation.

7.1.1 Artistic Performance Quality

When practicing artistic performance quality, participants make choices about the *dynamics*, or *kinetics*, with which they move, even when performing pre-set steps.

LWC's current work in iSCI locomotor rehabilitation has proposed[219] and substantiated[220–222] that movement dynamics mediate neuromotor learning. Additionally, artistic choice of movement dynamics performed may promote autonomy support (e.g., self-direction in task performance), shown to positively influence motor learning[94,223,224].

7.1.2 Improvisational Movement Generation

When practicing improvisational movement generation, participants spontaneously create new movements. In traditional and ballroom styles these manifest as "embellishments" and in improvisational dance pedagogy as "generative movement choices". Movement generation by non-dancers integrates the cortical and subcortical regions mediating cognitive, sensory, and motor function[129,130]. Integration of natural cognition and kinetics to perform creative acts has been argued to represent a primary factor in human evolution and progress[225,226] and likely influences motor learning.

7.2 SYNTHESIS OF THEORETICAL FRAMEWORKS

The Dynamic Systems perspective has impacted more fields of study than motor control. A rich history of scholarship seems to have developed from many perspectives, in parallel with scholarship from the motor learning perspective[227]. It would be worthwhile to examine the various perspectives on human skill acquisition in a holistic manner, to assess overlapping themes that might provide guidance for Neurorehabilitation. For instance, context as a driver of self-organizing behavior is explored from the perspectives of education studies (i.e., the Theory of Situated Learning[227]), management studies (i.e., the Theory of

Integrated Contextual Learning[228]), and Social Behavioral Dynamics (i.e., studies of synchronization in motor behavior between organisms[229]). Future research will seek to synthesize themes from the various perspectives that might inform Neurorehabilitation guidance.

7.2.1 Errorless vs Error-Augmented Training Paradigms

One area of interest with regard to synthesis of the literature involves reports of implicit learning as responding best to training conditions that are errorless[230–233] vs error-amplified[234–237]. This is an area of confusion that needs clarification in the context of Neurorehabilitation. Future work will seek to clarify guidance around when clinicians should reduce vs. amplify error in the domains of motor and cognitive Neurorehabilitation in order to promote explicit goals around implicit skill learning.

7.2.2 Playing for Neurorehabilitation

Another area requiring both synthesis between fields as well as future research in Neurorehabilitation is the area of *play.* Play (sections 2.2.2.4 and 2.2.3.3) potentially represents an ecologically valid means for Neurorehabilitation clients to explore their solution space. Different perspectives on learning theory seem to have independently converged on play as a solution to the serious problem of implicit skill learning. Important techniques have emerged from different perspectives. Play was pioneered by Mihaly Csikszentmihalyi[238] in the field of psychology. The Montessori method[239] is ubiquitous as a means to promote play-based learning within early childhood education. In the corporate world, Serious Play has been advanced by the Lego Company[240–242] as a practice in collective creativity and theater-based Improvisation has emerged as a team-building and leadership-training technique[243,244]. However, the playful approach to therapy design has yet to find a true foothold in evidence-based Neurorehabilitation practices. Future research will address the MRC model regarding investigating play as a form of complex intervention that might promote implicit engagement in explicitly defined Neurorehabilitation goals.

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Appendix A Candidate's full publication list (*presented for this thesis)

Worthen-Chaudhari L, Lamantia MT, Monfort SM, Mysiw W, Chaudhari AMW, Lustberg MB (2019) Partnered, Adapted Argentine Tango Dance for Cancer Survivors: a pilot study of efficacy. *Clinical Biomechanics, 70, 257-264.*

Hackney ME, **Worthen-Chaudhari L**, Abraham A, Bockbrader MB. Motor Cognitive Interaction: the role and measurement of engagement. *Journal of Functional Neurology, in press.*

Worthen-Chaudhari L, Monfort SM, Bland C, Pan X, Chaudhari AMW (2018) Characterizing within-subject variability in quantified measures of balance control: a cohort study. *Gait & Posture, 64,* 141-146 ***(Paper 5)**

Harvey R et al. (on behalf of the NICHE Trial Investigators including **Worthen-Chaudhari L)** (2018) Randomized Sham-Controlled Trial of Navigated Repetitive Transcranial Magnetic Stimulation for Motor Recovery in Stroke. S*troke, 49,* 2138-46.

Borstad A, Crawfis R, Phillips K, Lowes LP, Maung D, McPherson R, Siles A, **Worthen-Chaudhari L,** Gauthier L (2018) In-home Delivery of Constraint Induced Movement Therapy via Virtual Reality Gaming. *J Pat Cent Res & Rev, 5 (1).*

Worthen-Chaudhari L, McGonigal J, Logan K, Bockbrader MA, Yeates KO, & Mysiw WJ (2017). Reducing concussion symptoms among teenage youth: evaluation of a mobile health app. *Brain injury*, *31*(10), 1279-1286.

Worthen-Chaudhari L, Schmiedeler JP, & Basso DM (2015). Training conditions that best reproduce the joint powers of unsupported walking. *Gait & Posture* 41.2, 597-602. ***(Paper 4)**

Worthen-Chaudhari L, Basso M, Schmiedeler J, Bing J (2014) A New Look at an Old Problem: Defining Weight Acceptance During Human Walking at Different Speeds. *Gait & Posture* 39.1, 588-592. ***(Paper 3)**

Worthen-Chaudhari L, Whalen C, Swendal C, Bockbrader MA, Haserodt S, Smith R, Bruce MK, Mysiw W (2013) A feasibility study using interactive graphic art feedback to augment acute Neurorehabilitation therapy. NeuroRehabilitation 33.3, 481-490. ***(Paper 2)**

Lowes LP, Alfano LN, Yetter B A, **Worthen-Chaudhari L,** Hinchman W, Savage J, Samona P, Flanigan KM, & Mendell JR (2012). Proof of Concept of the Ability of the Kinect to Quantify Upper Extremity Function in Dystrophinopathy. *PLoS currents*, *5*.

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Van der Loos HFM, **Worthen-Chaudhari L**, Schwandt D, Bevly DM, Kautz SA (2010) A split-crank bicycle ergometer uses servomotors to provide programmable pedal forces for studies in human biomechanics. *IEEE Trans Neural Sys & Rehab* 18(4), 445-452.

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Bronner S and **Worthen L** (1999) The demographics of dance in the United States. *Journal of Dance Medicine and Science* 3(4), 151-153.

Appendix B Copies of publications included in the thesis.